



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**LITTORAL COMBAT SHIP (LCS) MISSION PACKAGES:  
DETERMINING THE BEST MIX**

by

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March 2008

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**LITTORAL COMBAT SHIP (LCS) MISSION PACKAGES: DETERMINING  
THE BEST MIX**

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Submitted in partial fulfillment of the  
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## **ABSTRACT**

The threat of a large fleet engagement in the open ocean is currently overshadowed by the asymmetric challenges presented by state and non-state actors using the littorals for illicit purposes. Unlike traditional multi-mission combatants, the Littoral Combat Ship (LCS) is a focused mission platform significantly less capable of handling simultaneous missions, whether they are planned or not. However, when deploying LCS as a squadron, a Combatant Commander may select to equip multiple LCS platforms with a mix of focused mission packages to ensure operational success across the broad range of challenges associated with littoral warfare. Through the use of simulation, design of experiments, and data analysis, this thesis simulated 41,195 littoral operations to address how many LCS should comprise an employed squadron, what the composition of a squadron should be, and how sensors and weapon systems contribute to the effectiveness of an employed squadron. The results indicate that a squadron size of six to ten LCS produces the best results, and that a compositional rule of thumb of five LCS for the primary threat and two LCS for the secondary threat applies to each warfare area. Lastly, the number of casualties suffered in each warfare area reinforces the danger associated with littoral combat and serves as a reminder that close engagement, while necessary, carries a cost.

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The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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## **LIST OF KEY WORDS, SYMBOLS, ACRONYMS AND ABBREVIATIONS**

ALFS	Airborne Low Frequency Sonar
ALMDS	Airborne Laser Mine Detection System
AMNS	Airborne Mine Neutralization System
ASW	Anti-Submarine Warfare
CNSF	Commander Naval Surface Forces
CONOPS	Concept of Operations
CSG	Carrier Strike Group
CSV	Comma Separated Value
DTA	Defense Technology Agency
EOD	Explosive Ordnance Disposal
ESG	Expeditionary Strike Group
JFC	Joint Force Commander
JHU APL	Johns Hopkins University Applied Physics Lab
LCS	Littoral Combat Ship
MANA	Map Aware Non-uniform Automata
MIO	Maritime Interdiction Operations
MIW	Mine Warfare
MOE	Measure of Effectiveness
NLOS	Non-Line of Sight
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
OASIS	Organic Airborne and Surface Influence Sweep
Pd	Probability of Detection
PGGF	Fast Attack Craft – Missile
Pk	Probability of Kill
RAM	Rolling Airframe Missile
RAMICS	Rapid Airborne Mine Clearance System

RMV	Remote Minehunting Vehicle
RMS	Remote Minehunting System
RTA	Remote Towed Array
RTAS	Remote Towed Active Source
SEED	Simulation Experiments and Efficient Designs
SUW	Surface Warfare
UAV	Unmanned Aerial Vehicle
UDS	Unmanned Dipping Sonar
UN	United Nations
USV	Unmanned Surface Vehicle
UTAS	Unmanned Towed Array System
XML	eXtensible Markup Language

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## **EXECUTIVE SUMMARY**

This thesis addresses the size, composition and effects of sensors and weapon systems of an employed Littoral Combat Ship (LCS) squadron in littoral combat. This summary gives an overview of LCS, describes the methodology of the research, and provides the resulting conclusions and recommendations. The goal of this research is to provide analytic support for the effective use of an employed LCS squadron.

LCS is a highly capable platform that promises to lead the Navy into the 21<sup>st</sup> century by providing access to the littorals, releasing multi-mission surface combatants for more appropriate tasking, and leveraging the technology of unmanned vehicles. The flexibility inherent in LCS allows it to operate independently, as part of an employed squadron, or as part of a Carrier or Expeditionary Strike Group (CSG/ESG). The ship's heavy reliance on technology and bold approach to manning has driven numerous studies to determine procedures, develop operational concepts, and identify best practices for LCS. Across all studies the mission of LCS remains constant; it must be able to ensure joint force access to the littorals. Unlike traditional multi-mission combatants, LCS is a focused mission platform significantly less capable of handling simultaneous missions, whether they are planned or not. However, when deploying LCS as part of a squadron, a Combatant Commander may select to equip multiple LCS platforms with a mix of focused mission packages to ensure operational success across the broad range of challenges associated with littoral warfare.

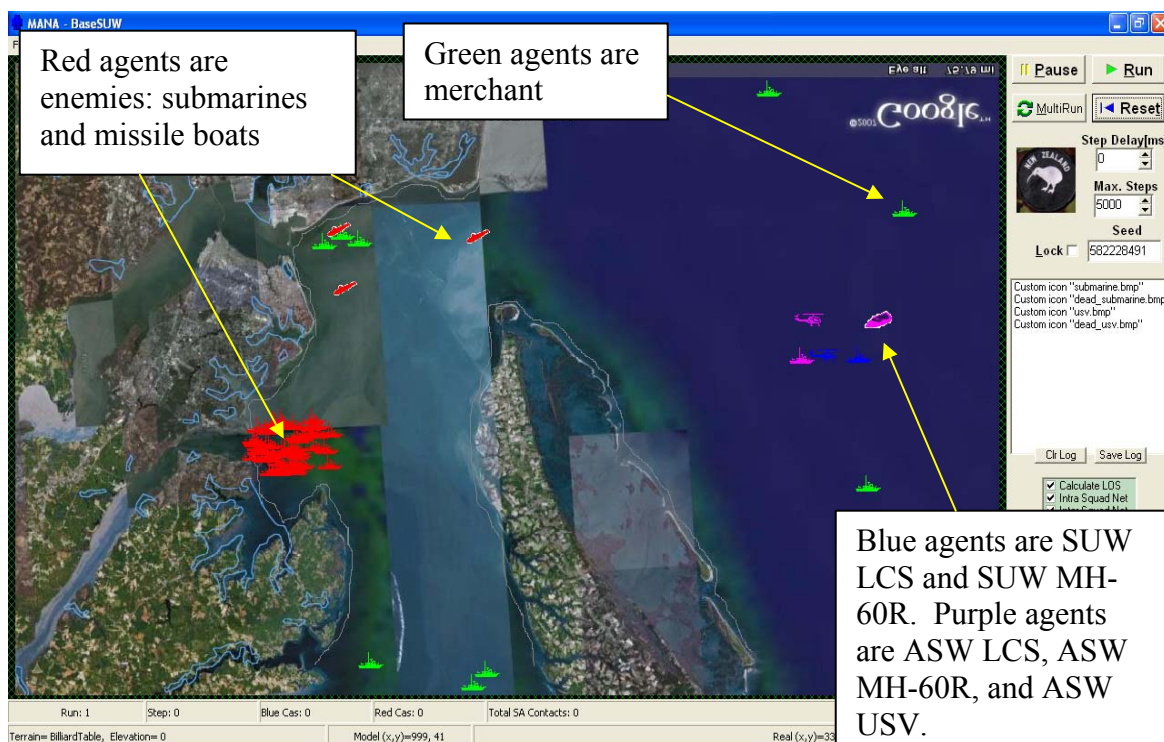
This analysis is guided by three questions to provide insight into the capabilities of an employed LCS squadron in a stressing operational environment. They are:

- How many LCS should there be in a squadron?
- What combination of mission packages is needed in the LCS squadron to complete the given focused mission when the possibility of multiple threats exists?
- How effective are sensors and weapon systems with regards to enabling LCS to complete its focused mission?

These questions are addressed using simulation, data farming techniques, and data analysis. In addition to providing insight into these questions, this thesis provides a

foundation for the use of simulation and data farming techniques for research on similar or related topics. The primary motivation for this thesis is to provide analytic support to determine the best configuration of an employed LCS squadron in order to complete a mission conducted in waters complicated by a broad range of threats.

In order to accurately address the questions driving this research, three robust scenarios were created based on the current mission packages for LCS: Surface Warfare (SUW), Anti-Submarine Warfare (ASW), and Mine Warfare (MIW). In each of these scenarios, an employed LCS squadron is deployed to neutralize a primary threat, but faces the possibility of a secondary threat in a different warfare area. For example, in the SUW scenario an employed LCS squadron is given a mission to neutralize a missile boat threat, but a submarine threat may exist in the same waters. An agent based combat modeling environment called Map Aware Non-uniform Automata (MANA) is used to implement these scenarios. The figure below shows a snapshot of the SUW scenario at problem start.



This simulation model uses a technique called data farming, which produces large amounts of data points through the use of high performance computing. This allows numerous variables (i.e., number of SUW LCS, number of missile boats, and probabilities of kill and detection for sensors and weapon systems) to be analyzed over broad ranges, providing insight into a large number of possible outcomes. Through this technique 41,195 littoral combat operations were simulated, 23,130 of which were used to produce the research data. These simulated operations were conducted in short order, and would have been costly and time consuming if conducted in real life.

Analysis of the simulation results addresses the questions posed by this thesis, and provides additional insights as well. With regards to the size of the employed LCS squadron, the analysis shows that a squadron size of six to ten LCS produces relatively low friendly casualties with high enemy casualties in all three warfare areas. Addressing the question of the composition of the employed LCS squadron, the analysis shows the following:

- Five SUW LCS and two ASW LCS produce low friendly casualties with high enemy casualties in the SUW scenario.
- Five ASW LCS and one SUW LCS produce low friendly casualties with high enemy casualties in the ASW scenario.
- Six MIW LCS and one SUW LCS produce low friendly casualties and high enemy casualties in the MIW scenario.
- Five LCS configured for the primary threat and two LCS configured for the secondary threat serves as a compositional rule of thumb

With regards to the effects of sensors and weapon systems, the analysis shows the following:

- Number of LCS is more significant than sensors and weapon systems in the SUW scenario.
- Hellfire Probability of Kill (Pk), Rolling Airframe Missile (RAM) Pk, SUW MH-60R Probability of Detection (Pd), ASW Unmanned Surface Vehicle (USV) Pd, and Blue Torpedo Pd are identified as playing a significant role in the ASW scenario.
- 57mm Pk is identified as playing a significant role in the MIW scenario due to it being the predominant SUW weapon on a MIW LCS.

While unable to provide precise thresholds for most of the sensors and weapon systems identified as significant, this thesis shows that certain systems play a significant role in the mission effectiveness of an employed LCS squadron.

Combining the results and insights produced by this thesis, the following recommendations are made:

- In order to produce low mean Blue casualties and high mean Red casualties, it is recommended the employed LCS squadron consist of six to ten LCS.
- When deploying an employed LCS squadron for an SUW mission that may contain a submarine threat, it is recommended that a composition of at least five SUW LCS and two ASW LCS be implemented.
- When deploying an employed LCS squadron for an ASW mission that may include a surface threat, it is recommended that a composition of at least five ASW LCS and one SUW LCS be implemented.
- When deploying an employed LCS squadron for an MIW mission that may include a surface threat, it is recommended that a composition of six MIW LCS and at least one SUW LCS be implemented.
- When considering the use of an employed LCS squadron for an ASW mission, it is recommended that additional fleet assets be provided to support the squadron if the expected number of enemy submarines is ten or more.
- When considering the use of an employed LCS squadron for a SUW mission that may contain a submarine threat, it is recommended that the squadron pursue the SUW threat using tactics that allow for the maximized use of ASW sensors and weapon systems.
- Due to the inherent risk of littoral combat, it is recommended that a paradigm shift occur in the U. S. Navy such that both ship and personnel casualties are expected and accepted.
- The use of simulation and data farming helped provide valuable insight in short order for an asset that is not yet deployable. It is recommended that simulation and data farming techniques be used in future U. S. Navy research to guide the development and deployment of new technologies.

This thesis provides analytic support for the size and composition of an employed LCS squadron based on a region and threat set, and identifies significant sensors and weapon systems for each warfare area. The result is sound analysis that can be used to assist the Navy in the continued development of policies, Concepts of Operation (CONOPS), and tactics for LCS and its mission packages.



## I. INTRODUCTION

*We cannot sit out in the deep blue, waiting for the enemy to come to us. He will not. We must go to him. I want the ability to go close in and stay there.\**

ADM Mike Mullen, USN

### A. OVERVIEW

Since the end of the Cold War, the threat facing the United States Navy has changed dramatically. Gone are the days where American naval operations were focused on defeating the growing Soviet challenge in blue water. Today, this challenge has been replaced by states that employ patrol boats, capable and quiet diesel submarines, sea mines, land-based anti-ship cruise missiles and other irregular means to deny access to U.S. forces attempting to influence events ashore. The threat of a large fleet engagement in the open ocean is currently overshadowed by the asymmetric challenges presented by state and non-state actors using the littorals for illicit purposes. Concurrently, industry has developed technologies that enable remotely controlled systems to operate over, on and below the water. The Navy realizes the operational potential of these systems and is working toward incorporating them into the fleet. This strategic transition and technological sea change have caused the Navy to revisit a force structure built on the premise of fleet engagement. Navy leadership determined that a ship able to operate in the littorals and take advantage of unmanned vehicles is a key component in maintaining an operational advantage at sea. The result is a frigate sized, modular, focused-mission platform called the Littoral Combat Ship (LCS).

With a smaller crew and a building cost less than current surface combatants, LCS provides the Navy an agile, adaptable platform that provides the near shore capability described by Admiral Mullen in his remarks at the Naval War College in August 2005. Its modular, focused-mission capability in Anti-Submarine Warfare (ASW), Surface Warfare (SUW), and Mine Warfare (MIW) allows the Combatant Commander to tailor

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\* Quote taken from "To Students and Faculty of the Naval War College," a speech given by Adm. Mike Mullen at the Naval War College, Newport, R.I. on 31 August 2005.

each LCS or LCS squadron to meet operational requirements. The Navy is still developing systems, procedures, and tactics for LCS and its unmanned vehicles using a process that requires frequent review to ensure operational suitability. In order to answer the demand signal for LCS, the Navy implemented a strategy of evolutionary acquisition with modular systems that may be adapted through spiral development to respond to evolving operational requirements. Implementing a modular open-architecture design enables capability insertion with greater agility, responding to fleet needs and opportunities stemming from maturing new technologies. This revolutionary process saves the Navy years in the acquisition process, but requires constant analysis to ensure continuity between what is required and what is developed.

## **B. BACKGROUND AND MOTIVATION**

LCS is a highly capable platform that promises to lead the Navy into the 21<sup>st</sup> century by providing access to the littorals, releasing multi-mission surface combatants for more appropriate tasking, and leveraging the technology of unmanned vehicles. The flexibility inherent in LCS allows it to operate independently, as part of an employed squadron, or as part of a Carrier or Expeditionary Strike Group (CSG/ESG). The ship's heavy reliance on technology and bold approach to manning has driven numerous studies to determine procedures, develop operational concepts, and identify best practices for LCS. Across all studies the mission of LCS remains constant; it must be able to ensure joint force access to the littorals. The primary motivation for this thesis is to provide analytic support for determination of the best configuration of an LCS squadron in order to complete a mission conducted in waters complicated by a broad range of threats.

Due to fundamental differences in manning concepts and platform configuration, a study of LCS must be approached differently than one examining legacy combatants. The policies, strategies, and tactics used to direct employment of traditional multi-mission platforms do not necessarily apply to LCS. These differences, coupled with a general misunderstanding of the LCS concept, have resulted in questions regarding the capability and operational utility of LCS. With the vision that LCS would require a shift in operational paradigm within the Navy, Commander Naval Surface Forces (CNSF)

issued a set of “cardinal rules” that are to be applied to LCS. These rules specifically state that multi-mission capability for LCS should not be sought, and that LCS cannot be compared to legacy platforms. (Commander Naval Surface Forces, 2007) While these statements highlight significant differences between LCS and current fleet surface combatants, both share the task of operating in dangerous and unpredictable environments. Unlike traditional multi-mission combatants, LCS is a focused mission platform significantly less capable of handling simultaneous missions, whether they are planned or not. However, when deploying LCS as part of a squadron, a Combatant Commander may select to equip multiple LCS platforms with a mix of focused mission packages to ensure operational success across the broad range of challenges associated with littoral warfare.

The ability of LCS to establish littoral dominance does not benefit the Navy alone, especially as the military becomes an increasingly joint organization. The importance of littoral warfare to the joint force was understood by the military as early as World War II, and was used extensively in the Pacific Theater to secure islands such as Guadalcanal. (Dunnigan and Nofi, 1995) This importance has been re-emphasized by stating:

Maintaining battlespace dominance will remain essential to the Joint Forces Commander (JFC) if forces ashore are to maintain their freedom of action. This means that battlespace control over a substantial littoral area must be secure and maintained long enough to successfully project combat power ashore to achieve the JFC’s objectives. (Joint Requirements Oversight Council, 2004)

This statement suggests that accessing the littorals alone is not sufficient, as this would only provide the joint force with temporary security and operational freedom. This tenet also applies to LCS operations in support of larger strike groups. To be a reliable asset to the Navy, an LCS squadron must be able to perform various missions in the littorals in the face of a multi-dimensional threat. Figure 1 illustrates how LCS will be used to gain and maintain access to the littorals. While much analysis has been done on the ability of LCS to perform certain individual missions, its efficiency in executing those missions in an environment that may contain more than one threat requires further exploration.

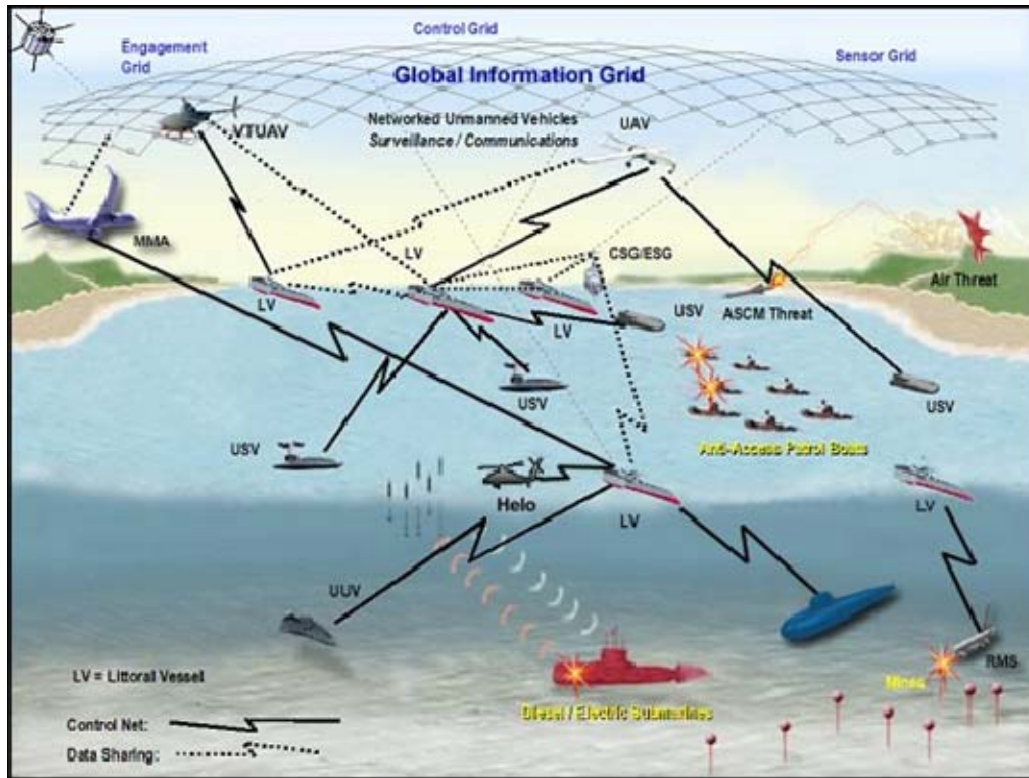


Figure 1. Pictorial display of the concept of LCS operations (from Joint Requirements Oversight Council, 2004)

### C. RESEARCH QUESTIONS

The goal of this thesis is to analyze LCS mission capabilities in an environment that presents a broad range of threats—both traditional in nature and those driven by irregular tactics. While this analysis cannot account for all possible scenarios or environments, the following questions guide this research:

- How many LCS should there be in a squadron?
- What combination of mission packages is needed in the LCS squadron to complete the given focused mission when the possibility of multiple threats exists?
- How effective are sensors and weapon systems with regards to enabling LCS to complete its focused mission?

This thesis uses simulation, data analysis, and other analytical methods to investigate these questions and develops a methodology to determine the best configuration of a LCS squadron. This is done for a given region based on the threats that may exist.

#### **D. BENEFITS OF THE STUDY**

This thesis provides the U.S. Navy analytical support for the continued development of policies, concepts of operations (CONOPS), and tactics for LCS and its mission packages. Additionally, this study provides insight into the capabilities of both an individual LCS and an LCS squadron when operating in an environment that presents a wide range of operational challenges. Ultimately, this thesis provides the Navy a methodology to determine the best configuration of an LCS squadron to successfully support joint force operations in an environment rife with asymmetric or irregular challenges.

#### **E. METHODOLOGY**

Using several analytic techniques, this thesis develops a means by which the Navy can evaluate operational configurations of an LCS squadron engaged in a variety of mission areas. Quantifiable measures of effectiveness (MOEs) for all three mission areas are identified and used to determine size and composition of an employed squadron. (Morris, 2000) Design of experiments techniques are used to vary the probabilities of detection, and kill for each sensor and weapon system in the mission packages. In order to evaluate its performance in a stressing operational environment, an agent-based computer simulation is used to place LCS in numerous scenarios that contain multiple threats.

This thesis uses an agent-based distillation—a type of computer simulation that attempts to model only the salient features of a situation and not every possible characteristic. (Cioppa, Lucas, and Sanchez, 2004) The tool used is Map Aware Non-uniform Automata (MANA), a product developed by New Zealand's Defense Technology Agency (DTA). The methodology is to develop scenarios that present a range of threats for each mission area. These scenarios are then replicated in the

simulation tool and the performance of LCS is analyzed. Exploratory analysis, or data farming, then identifies previously undetermined characteristics and situations that develop during the simulations. (Cioppa, Lucas, Sanchez, 2004) Statistical analysis and other analytic techniques identify and determine the importance of interactions between variables and lead to understanding the significance of the data. The results of the statistical analysis help identify the best configuration of an LCS squadron for each scenario. Through quantitative analysis, this study enhances understanding as to how to best configure an LCS squadron for a given region and threat set.

## **II. MODEL DEVELOPMENT**

### **A. INTRODUCTION**

In order to accurately capture how LCS will perform in a stressing operational environment, robust scenarios that contain both the primary threat associated with each mission package and a realistic secondary threat are required. In this chapter, a brief introduction of LCS will be given as well as descriptions of the scenarios used for this thesis. After covering the scenarios, a brief description of the MANA simulation tool used to model LCS is provided. Lastly, this chapter describes in detail how the simulation model behaves.

### **B. WHAT IS THE LITTORAL COMBAT SHIP?**

#### **1. Overview**

Chapter one gives a brief description of LCS, however, a detailed look is required to fully realize its potential. Flexibility is the defining characteristic of LCS—the ability to operate in the littoral areas as part of a Carrier Strike Group (CSG) or Expeditionary Strike Group (ESG), multi-national force, or individually while bringing to bear capabilities needed for a specific mission. The objective of the LCS concept of operations is to allow the U.S. Navy to reduce the number of sailors in closely contested areas and maximize asset allocation for the rest of the surface force. The source of this flexibility resides in the seaframe concept:

The attribute that differentiates the LCS from previous surface combatants is its role as a “seaframe”, serving much the same purposed as a reconfigurable airplane or helicopter airframe. It incorporates open architecture mission packages that connect to core support systems and can be changed or modified in a short period of time. (Commander Naval Surface Forces, 2007)

The seaframe is augmented by mission packages that are focused in one of three mission areas: Surface Warfare (SUW), Anti-Submarine Warfare (ASW), or Mine Warfare (MIW). Each mission package contains mission modules that are comprised of different mission systems, illustrated by Figure 2. Due to the evolutionary nature of LCS

procurement, a snapshot of the seaframe and mission packages is required to perform this analysis. The snapshot chosen for this work is the Warfighting Concept of Operations Revision Alpha, dated 14 March 2007. This section provides a detailed look into the seaframe as well as the primary mission packages being developed for LCS.

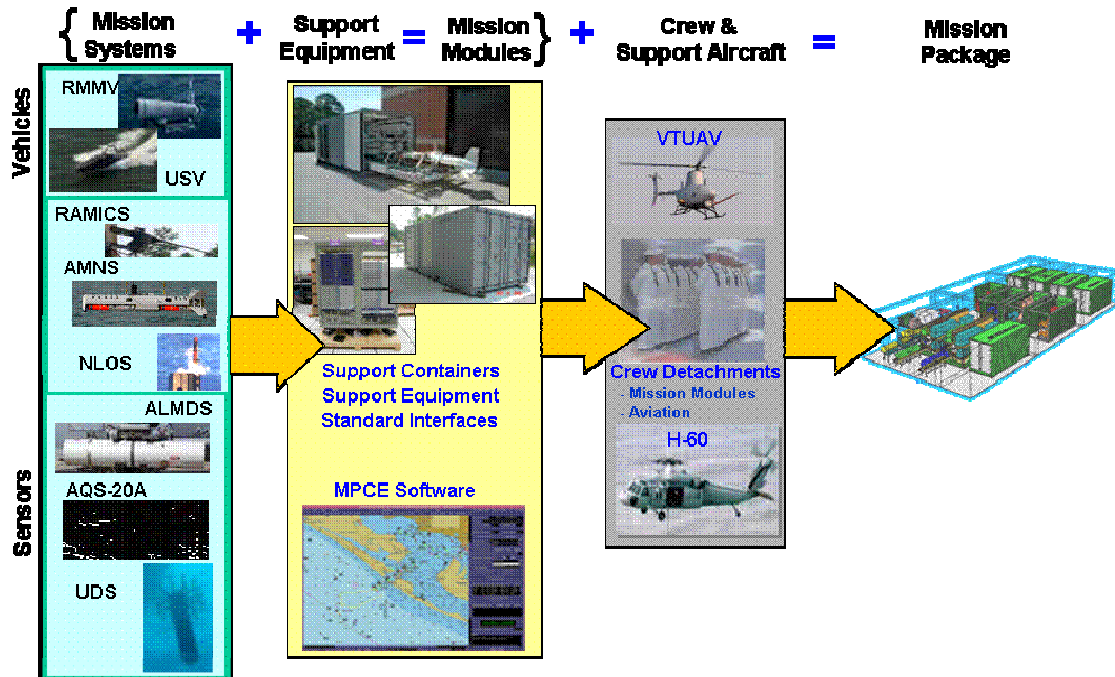


Figure 2. Composition of a mission package (from PMS 420, 2008)

## 2. Seaframe

As the core of LCS, the seaframe provides basic self defense capability through organic sensors, weapons, and speed. While two seaframe designs are still being considered, both are capable of attaining speeds over 40 knots and are similarly equipped regarding organic weaponry. There are differences between the competing seaframes, but they are not the focus of this work. Instead, the focus is on the weapons and systems of LCS and its mission packages. While the two seaframes use different point defense missile systems, the Rolling Airframe Missile (RAM) Block 1 air defense missile system is being modeled in this thesis based solely on the number of missiles provided. Figure 3 shows the sensors and weapons used for the seaframe in this thesis.



<b>Seaframe Sensors and Weapons</b>	<b>Quantity</b>
Three-dimensional air/surface search radar with periscope detection capability	1
EO/IR mast-mounted sensor	1
Mk-3 57mm gun	1
Crew-served .50-caliber guns	4 mounts
RAM Block 1 air-defense missile (LM)	1 launcher (21 missiles)
SeaRAM missile system (GD)	1 launcher (11 missiles)

**(UNCLASSIFIED)**

Figure 3. Sensors and weapons for the LCS Seaframe (from Naval Warfare Development Command, 2007)

### **3. Mission Packages**

The mission packages form the bulk of the warfighting capability of LCS. Three warfare areas have been identified as immediately necessary: SUW, ASW, and MIW. The possibility of additional mission package types is being considered by the navy, but the focus of this thesis is on the initial mission packages.

#### ***a. Surface Warfare (SUW)***

Designed to detect and engage multiple targets in the littorals, the SUW mission package strengthens the core seaframe capability by adding a helicopter armed with Hellfire missiles, two 30 millimeter guns, and the Non-Line of Sight (NLOS) missile system. (Joint Requirements Oversight Council, 2004) While the MH-60S is listed as a possible part of the SUW mission package, this thesis models the MH-60R. The SUW mission package combined with the speed of LCS provides the Navy a credible asset to use against surface threats in the littorals. Figure 4 shows the systems and weapons contained in the SUW mission package.

<b>SUW Modular Elements</b>	<b>Qty</b>
Vertical Take-Off Unmanned Aerial Vehicle (VTUAV)	2
EO/IR/LD sensor and datalink relay	1
MH-60R/S	1
GAU 16/19 machine gun	1 (60R) or 2 (60S)
Hellfire missiles	8
Non-Line-of-Sight Launch System (NLOS-LS) missile system	60 (4 launchers with 15 missiles each)
Laser designator for NLOS-LS missiles	1
Mk 46 Mod 1 30mm gun system	2
57mm gun system (Not a modular component)	1

**(UNCLASSIFIED)**

Figure 4. Systems and weapons contained in the SUW mission package (from Naval Warfare Development Command, 2007)

***b. Anti-Submarine Warfare (ASW)***

The ASW mission package takes advantage of off board technology in the search, localization, and prosecution of enemy submarines. With the inclusion of unmanned vehicles, the ASW configured LCS is capable of sweeping and maintaining barriers or operating areas while reducing the risk of casualties. Both the unmanned surface vehicles (USVs) and the remote minehunting vehicles (RMVs)—configured for ASW—employ either towed array or dipping sonar payloads. The USVs employ a dipping sonar similar to that used by the MH-60R Helicopter also included in the ASW mission package. The tactic used by a dipping sonar, known as sprint and drift, is not easily modeled in MANA. As such, an average search rate was determined for both the MH-60R and the USVs in order to model the effects of the sprint and drift tactic. The RMVs operate differently from the USVs in that the former must operate as a pair. With one RMV towing an active source and the second towing a passive towed array, the pair provides a bistatic sonar capability. (Naval Warfare Development Command, 2007) Unlike the SUW LCS which can fire or launch several SUW weapons, the ASW LCS does not have an anti-submarine weapon that is capable of being delivered by the LCS.

Instead, the ASW LCS relies on the MH-60R deploying Mk 54 torpedoes in order to neutralize the enemy. Figure 5 shows the weapons and systems contained in the ASW mission package.

<b>ASW Modules</b>	<b>Qty</b>
USV with ASW Systems	2
UDS	1
UTAS	1
MH-60R with	1
Mk 54 Torpedo	Set
ALFS	Set
Sonobuoys	Set
RMV with ASW Systems	2
RTA (MFTA)	1
RTAS	1

**(UNCLASSIFIED)**

Figure 5. Systems and weapons contained in the ASW mission package (from Naval Warfare Development Command, 2007)

*c. Mine Warfare (MIW)*

The MIW mission package, recognized as the most needed due to the aging of the Navy's current mine countermeasure force, also takes advantage of unmanned vehicle technology. Similar to the ASW mission package, the MIW mission package is dependent on its MH-60S helicopter for neutralization of detected mines. While Explosive Ordnance Disposal (EOD) personnel may be available for mines not capable of being neutralized by the MIW LCS, they are not being considered in this thesis. The USVs and Remote Minehunting Systems (RMS) in the MIW mission package all use towed bodies to counter mines, but the RMSs in the MIW mission package work independently. The MH-60S has several different weapons to neutralize different types of mines, but it is only able to carry one system at a time. This capability

is abstractly modeled in order to focus on the overall system effectiveness and not the performance of specific weapons. Figure 6 shows the systems and weapons that are contained in the MIW mission package.

<b>MCM Package Elements</b>	<b>Qty</b>
Unmanned Surface Vehicle (USV) (initially based upon 11-meter RHIB)	1
Vertical Takeoff Unmanned Aerial Vehicle (VTUAV)	1
Coastal Battlefield Reconnaissance and Analysis (COBRA)	2
MH-60S	1
Organic Airborne and Surface Influence Sweep (OASIS)	1
AN/AQS-20A Minehunting Sonar Set (helicopter-configured)	1
Airborne Laser Mine Detection System (ALMDS)	1
Rapid Airborne Mine Clearance System (RAMICS)	1
Airborne Mine Neutralization System (AMNS)	1
Remote Minehunting Vehicle/System (RMV/RMS)	2
AN/AQS-20A Minehunting Sonar Set (RMV-configured)	2

**(UNCLASSIFIED)**

Figure 6. Systems and weapons contained in the MIW mission package (from Naval Warfare Development Command, 2007)

#### **4. Additional Capabilities**

While three mission packages have been identified as immediately necessary, other capabilities currently exist and additional needs may present themselves in the future. For example, LCS has inherent Maritime Interdiction Operations (MIO) capabilities and the possibility of a special forces capable mission package is being considered. (Commander Naval Surface Forces, 2007) The creation of additional mission packages is not limited to special forces, but is being considered for a broad range of operations. The modular flexibility of LCS allows for additional mission packages as necessary, as well as creating variations to existing mission packages which may save cost or better meet operational needs. This ability to create new mission packages to address a new threat instead of new platforms is one of the strengths of the LCS program.

## **C. DESCRIPTION OF SCENARIOS**

In order to gain insight into the necessary mix of a LCS squadron in an environment that may contain multiple threats, scenarios are developed for each of the three mission areas. These scenarios contain the primary threat associated with each mission package and an additional threat that is associated with one of the other LCS mission packages. This section explains the three different scenarios in detail.

### **1. SUW Scenario**

A CSG is preparing to transit a strait in a contested region. A threatening nation disapproves of the CSG's presence in what it claims as its territorial waters, and is determined to take actions necessary to prevent the transit. Intelligence reports suggest that the possibility of the CSG being attacked by missile boats is high, but the number of possible attackers is unknown. Intelligence reports further stipulate that enemy submarines may be underway in the strait, and could support the missile boat attack. The locations of the missile boat threat and possible submarine threat are unknown.

#### ***a. Enemy***

Missile boats deployed in the strait have been ordered to attack any U.S. vessels detected. Due to their individual vulnerability and cumulative strength, missile boats usually travel and attack as a group. While submarines may or may not be underway in the strait, submarines that are in the strait have been ordered to patrol the entrance of the strait and to engage any U.S. vessel trying to gain entrance.

#### ***b. Friendly***

The employed LCS squadron will vary in its size and allocation of mission packages. If an ASW LCS is included in the squadron it will only use its MH-60R and USV for detection and prosecution of submarines due to the speed necessary for timely completion of the mission. The squadron will transit the strait at 20 knots with its respective helicopters deployed, while searching for missile boats. This allows the use of

the ASW MH-60R as a both a scout and pouncer for enemy submarines if an ASW LCS is included in the squadron, and uses the SUW MH-60R as a scout for early detection of missile boats.

### c. *Mission*

The mission of the employed LCS squadron is to clear the strait of any missile boat threats in order to provide a safe transit for the CSG, while minimizing the number of friendly casualties. Any detected submarines will be considered as supporters of the missile boat threat, and viewed as targets of opportunity. Figure 7 shows the SUW scenario at problem start.

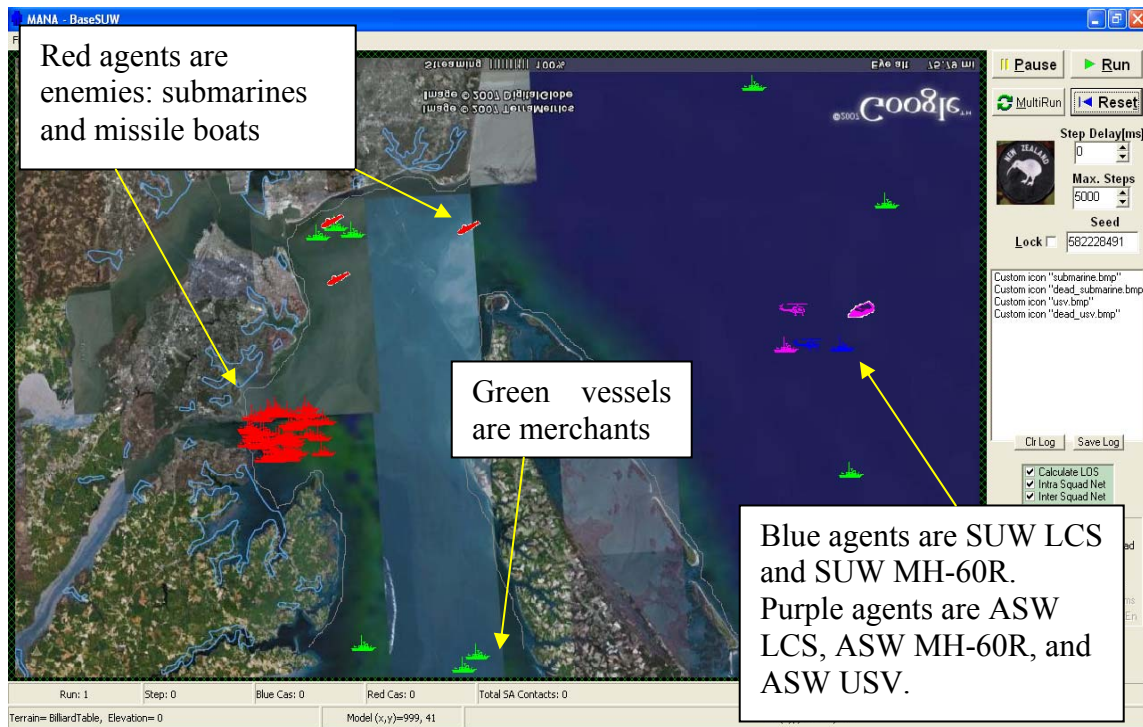


Figure 7. Screen shot of SUW Scenario at problem start.

## 2. ASW Scenario

An ally of the U.S. has raised concern over the increase of naval activity by its neighbor in an adjacent strait. This strait separates the ally from its neighbor, and the ally views the increase of activity as a sign of hostile intent. As such, the ally has requested

increased support from the U.S. both politically and militarily. Political attempts have failed to de-escalate the situation, and a CSG has been deployed to the strait in order to protect both U.S. interests in the strait and its ally. Intelligence reports that the increase in enemy naval activity has been primarily through the deployment of submarines, but that some missile boats may have been deployed as well. An LCS squadron has been deployed to arrive in advance of the CSG.

***a. Enemy***

Submarines deployed in the strait have been ordered to patrol at slow speeds and to engage any contact deemed hostile regardless of nationality. Each submarine is steaming independently in order to maximize the amount of water covered. Any missile boats that are deployed in the strait have been ordered to intercept surface vessels or aircraft deemed as hostile, with the act of searching for submarines included as a sign of hostile intent. Due to their individual vulnerability and cumulative strength, missile boats transit and attack as a group.

***b. Friendly***

In order to clear the strait of enemy submarines, the employed LCS squadron transits with its USVs, RMVs, and helicopters deployed. The squadron steams at 12 knots in order to provide the best search speed for its off board vehicles. The size and composition of the LCS squadron will vary. If a SUW LCS is included in the squadron its SUW MH-60R will serve as a scout, increasing the range of detection for any missile boats. The ASW MH-60R will serve as a pouncer, prosecuting enemy submarines that are detected by the off board vehicles.

***c. Mission***

The LCS squadron will clear the strait of enemy submarines while minimizing friendly casualties. Any detected missile boats are considered hostile and viewed as targets of opportunity. Figure 8 shows the ASW scenario at problem start.

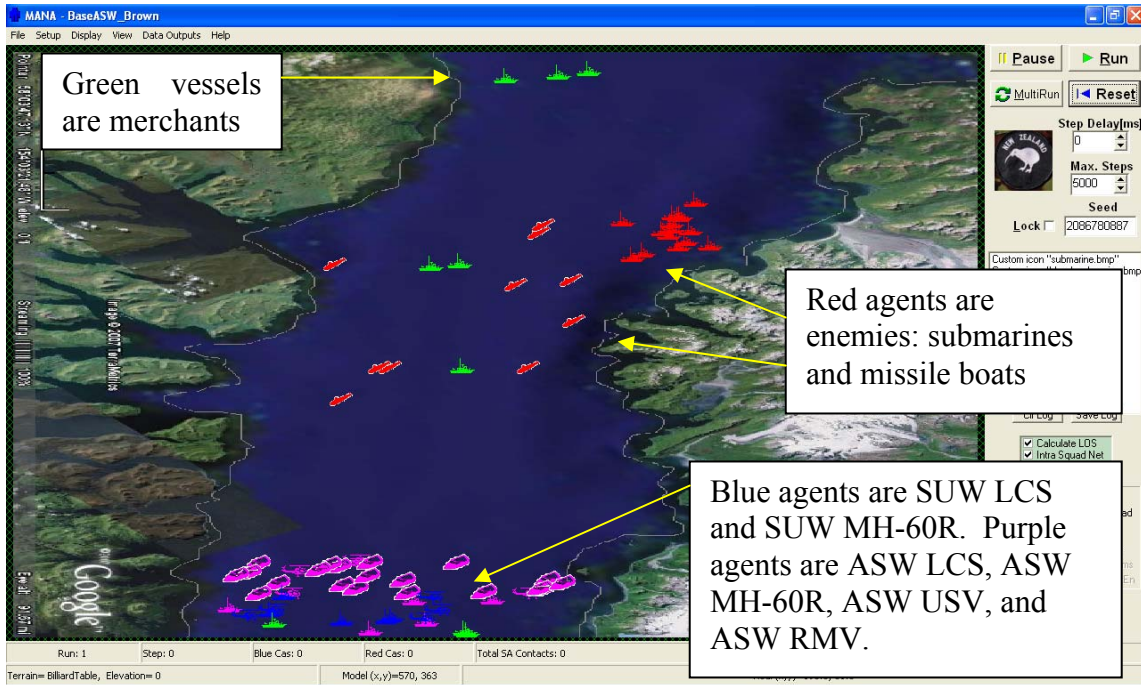


Figure 8. Screen shot of ASW Scenario at problem start.

### 3. MIW Scenario

Desiring to wreak havoc on the world's economic system, a rogue nation has mined a strait that is a vital shipping lane. The United Nations (UN) has agreed to economically sanction the rogue nation, but a coalition for military engagement could not be agreed upon. Severely affected by the loss of the shipping lane, the U.S. has deployed an LCS squadron in order to regain shipping access to the strait. Intelligence reports cannot confirm the number of mines used or their location, but do suggest that missile boats may be used by the rogue nation to counter mine clearance operations.

#### a. *Enemy*

Numerous mines have been deployed in a column across the width of the strait. All missile boats deployed to the strait have been ordered to engage any vessel or aircraft that attempts to clear the mines or displays unusual behavior. Due to their individual vulnerability and cumulative strength, missile boats transit and attack as a group.



**b. Friendly**

Since the LCS squadron is not aware of the location of the mines, the USVs, RMSs, and helicopters will be deployed throughout the transit of the strait. The squadron transits at 12 knots in order to employ the off board vehicles at their best search speed. The size and composition of the LCS squadron varies. The MIW MH-60S search for as well as neutralize detected mines, while the SUW MH-60R serves as a scout for any missile boats if an SUW LCS is assigned to the squadron. The detection of mines by the helicopter or the off board vehicles is passed to all units in the squadron to prevent inadvertent entering of the mine field.

**c. Mission**

The LCS squadron desires to clear the strait of mines while minimizing friendly casualties. Any detected missile boats are considered attempts to re-mine the strait, and will be engaged when detected. Figure 9 shows the MIW scenario at problem start.

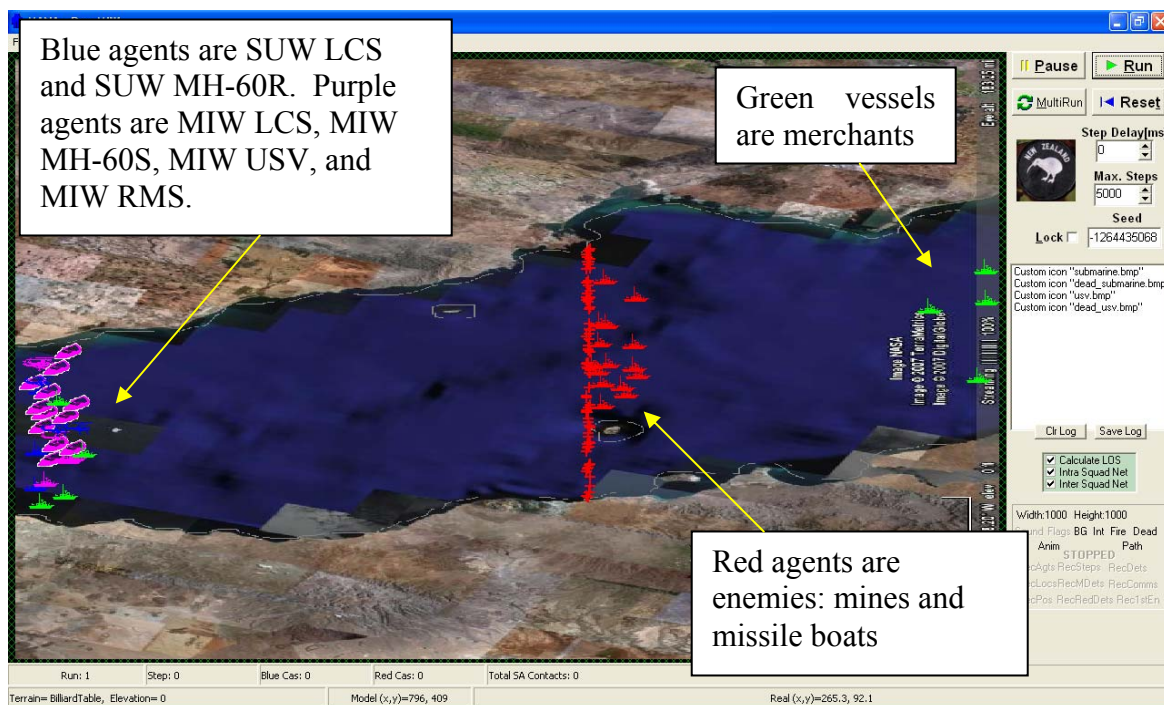


Figure 9. Screen shot of MIW scenario at problem start.

## **D. THE MANA COMBAT SIMULATION TOOL**

Having described the scenarios, this section discusses the combat simulation tool. An agent based distillation called Map Aware Non-uniform Automata (MANA) was selected as the model best suited for this work; this section explains how that decision was made.

### **1. Choosing MANA**

This research started during an experience tour at Johns Hopkins University Applied Physics Lab (JHU APL). While there, an agent based model called Sim Tool was introduced for possible use in this thesis. Sim Tool was developed by JHU APL, and the fact that it already contained several agent personalities, sensors and weapon systems similar to that of LCS made its use attractive. JHU APL was kind enough to release a copy of Sim Tool to the Naval Postgraduate School (NPS) for use in this thesis, with the potential of further development of Sim Tool through troubleshooting. As the research progressed it was discovered that alterations to the pre-programmed attributes in Sim Tool were necessary, which caused a problem regarding timing. While working with the Sim Tool programmers on a few alterations, other agent based combat models were being considered in the event that the use of Sim Tool would become no longer viable.

MANA is a combat model developed and given to NPS by New Zealand's Defense Technology Agency (DTA); it is user friendly and well documented. It is an excellent quick turn around tool—in MANA a generic scenario to model numerous outcomes can be quickly generated. Agent personalities, sensors, weapons, and various other parameters are easily manipulated and, more importantly, MANA lends itself to data farming. When the use of Sim Tool became too time consuming, these capabilities were major contributors in the decision to use MANA as the combat model for this thesis.

### **2. MANA Characteristics**

Designed by New Zealand's Defense Technology Agency (DTA) to research complexity and chaos in combat, MANA is an agent based distillation that uses entities able to make their own decisions to explore the essence of a given problem (Galligan,

Anderson, and Lauren, 2004). This independent decision making capability is achieved through the use of situation awareness maps, and establishing an agent's personality—how it responds to what it sees. MANA's bottom up approach facilitates modeling problems in a broad range of detail, depending on the needs of the user. While MANA version 4.0 has been recently released, version 3.0.39 was used for this thesis due to the possibility of bugs in MANA 4.0. The MANA User's Manual provides much more information regarding MANA's uses, characteristics, and capabilities. Figure 10 shows the start up screen for MANA which provides reference information.

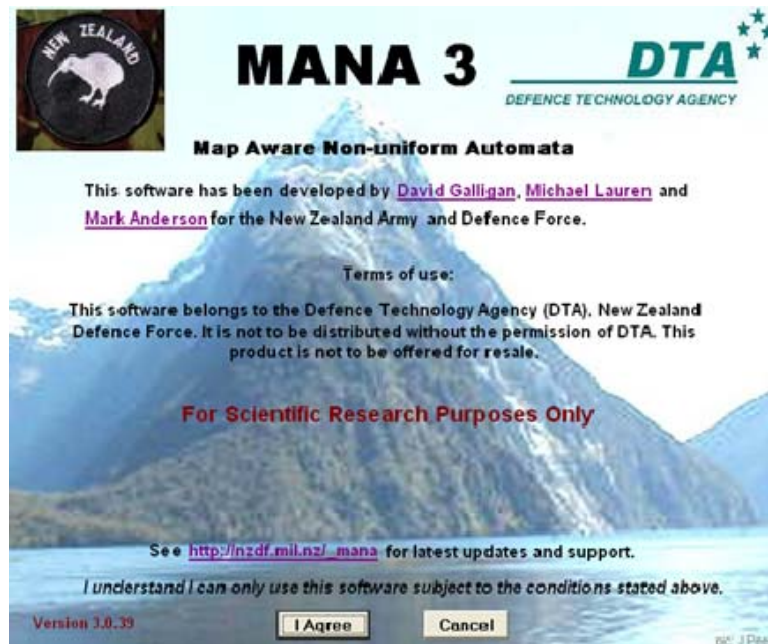


Figure 10. Screen Shot of MANA start up screen. Website contains more reference material.

## E. CHARACTERISTICS OF THE SIMULATION MODEL

The focus of this section is to provide the characteristics of the MANA model created for this research in terms that are easily understandable. The goal of the simulation is discussed followed by the terrain and scale, the enemy forces, and friendly forces. Finally, the issues of sources of data, abstractions, and assumptions are addressed. A detailed breakdown of the personalities and capabilities of the enemy and friendly forces can be found in Appendix A.

## **1. Simulation Goal**

The scenarios used in this thesis are designed to stress each mission package in order to gain insight into the size and possible composition of an employed LCS squadron. This being the case, LCS and its mission packages are abstractly modeled and the primary measure of effectiveness is not the number of enemy killed, but the number of friendly casualties. The factors that play an important role in this simulation are the number of enemy platforms, the number and type of LCS, the probability of detection for the friendly sensors, and the probability of kill for friendly weapons. Using design of experiment techniques, these factors are explored over large ranges to determine which factors are important and at what levels.

## **2. Terrain and Scale**

MANA is a time step model that requires a coupling of simulation time and real time, as well as the simulation world and the real world. In this simulation, each time step is equal to 30 seconds. Each scenario lasts no longer than 5,000 time steps, which is slightly less than 48 hours. The simulation map is 1,000 pixels by 1,000 pixels corresponding to a real world map of 335 nautical miles by 225 nautical miles. This produces a pixel to nautical mile ratio of about 3:1, which provides for accurate modeling of agent movements. This means that each pixel is approximately equivalent to 1/3 of a nautical mile. If large pixels to nautical mile ratios are used, agents could move in unrealistic ways. The above couplings results in a single run lasting anywhere from 7 to 90 minutes on computers with processor speeds ranging from 448 MHz to 3.19 GHz. The source of variation in these run times is the number of agents involved in that given run.

MANA provides the ability to model various types of terrain, including hilltops, light and dense brush, roads, and walls. Since these scenarios are all nautical, terrain is not used with the exception of the wall and hilltop feature. The wall feature is used to prevent ships and submarines from sailing on land, and the hilltop feature is used in the SUW scenario to prevent agents from detecting and engaging each other over a peninsula. To achieve this, a terrain map is built by selecting the desired area map and

then using the MANA Scenario Map Editor to line the land in the map with the wall feature, and covering the peninsula with the hilltop feature. This terrain map is used by the agents to assess situational awareness. The different terrain features are assigned different colors in MANA; gray is the color for the wall feature and dark gray identifies the hilltop feature. Figure 11 shows the terrain and background maps.



Figure 11. Terrain (left) and Background (right) maps used in the SUW scenario. The gray lining the land on the terrain map is the wall feature and the dark gray covering the peninsula is the hill top feature.

The terrain map is not the map seen by the user while conducting runs; what is seen is the background map. This allows the user to show a recognizable real world map during simulations without affecting the agent's simulation awareness. Essentially, the terrain map is for the agents and the background map is for the user.

### **3. Enemy Forces**

Each type of enemy is assigned a home position where they start the scenario. Submarines will independently patrol this position until they detect an enemy or take fire. Submarines will pursue a detected friendly agent and will evade if fired upon by increasing speed and taking random courses away from friendly forces. These traits are also used by missile boats with minor variations. While missile boats do not patrol, they transit and attack as a group for safety and cumulative strength. When a friendly agent is detected the missile boats will pursue, and when taking fire the missile boats will try to

evade while pursuing and engaging the friendly agent. Mines used in this simulation simply detonate whenever an agent comes within a specified range.

#### **4. Friendly Forces**

Like the enemy forces, friendly forces are assigned a home position as well as waypoints specific to each scenario. Each variant of LCS transits from the home position through the waypoints engaging detected enemies when they are capable. In the ASW and MIW scenario the waypoints are loosely followed to allow search of the entire strait. The helicopters associated with the mission packages transit along with the LCS according to their speeds, and will pursue and engage enemies detected. Fuel consumption is modeled for the helicopters, with the SUW MH-60R needing to refuel every 3.5 hours, and the ASW MH-60R and MIW MH-60S requiring refueling every 3 hours due to their search tactics. During their refueling, which lasts 45 minutes, none of the helicopters can detect or engage enemies. The off board vehicles behave similar to the helicopters, with the exception of engaging enemies and fuel. None of the unmanned off board vehicles carry weapons, which limits them to pursuing the enemy and passing this detection to their respective LCS. Since the SUW mission package adds two weapon systems to the LCS, the .50 caliber weapons are not modeled for the SUW LCS. This is due to MANA's limitation of four weapons per agent.

#### **5. Sources, Abstractions, and Assumptions**

With every simulation, the source of input data and assumptions are quite important. In this simulation, communications and logistics are assumed to work perfectly. This is to say that, regarding logistics, the location and number of available mission packages is not considered, and fuel (with the exception of helicopters) is unlimited. Failure of equipment and maintenance are also not considered in this simulation.

Enemy force sensor and weapon information, number of weapons per enemy agent, and capabilities of certain friendly sensors and weapons were taken from Jane's Fighting Ships 2006, All the World's Aircraft 2006, and Underwater Warfare Systems 2005. The probabilities associated with enemy sensors and weapons were generalized

and reviewed by Dr. Tom Lucas, Ph.D., combat modeling expert at NPS, Jeff Kline, retired Navy Captain and Chair of Warfare Innovation at NPS, CAPT Mike Good, USN, Program Manager, LCS Mission Modules, and LCDR Bill Harrell, USN, Assistant Program Manager, MIW Mission Modules.

Both the ASW MH-60R and the ASW USV use a dipping sonar to detect submarines; a tactic known as “sprint and drift.” Since this tactic is not easily modeled in MANA, effective search rates were developed as an abstraction. The search rates are based on 5 minutes lowering the sonar, 5 minutes operating the sonar, 5 minutes hoisting the sonar, and 5 minutes sprinting to the next search area. The search rates result in an aggregate speed of 20 knots for the ASW MH-60R and 12 knots for the USV. These search rates, as well as the refueling information for the helicopters were validated by Jeff Kline, and CDR Doug Burton, USN, Military Instructor at NPS and SH-60B pilot. The speed used for the MIW MH-60S was validated by LCDR Dale Johnson, USN, MH-53 pilot and Operations Research student at NPS. This model assumes that each LCS chooses to operate with its armed helicopter deployed. This being the case, Unmanned Aerial Vehicles (UAVs) contained in the mission packages are not modeled. Characteristics and capabilities of LCS and its off board vehicles were provided by CAPT Mike Good and LCDR Bill Harrell. The number of enemy and friendly agents, as well as the probabilities associated with the friendly sensors and weapons are explored through design of experiment techniques that will be discussed in the next chapter. The ranges over which these parameters are explored were reviewed by Dr. Lucas, Captain Kline, and Colonel Ed Lesnowicz, retired Marine artillery officer with Wisdom Jacket Consulting.

Very rarely does a simulation tool perfectly fit the problem being modeled. Frequently, modeling issues are discovered during the model development process and are either fixed through the developers of the tool or addressed through other modeling work arounds. In this thesis, two such modeling issues were discovered. The first modeling issue is the ability of the ASW LCS to detect submarines at the range of its surface search radar. This occurs because, in MANA, the submarines are modeled as surface contacts and the non-ASW capable assets are programmed to ignore this specific

threat. ASW capable assets, however, are programmed to engage any detected submarines. In order to work around this modeling issue, ASW LCS were not allowed to pass submarine contacts to its ASW MH-60R and were given a stand off distance of 10 nautical miles from detected submarines. This prevented the ASW LCS from engaging submarines from unrealistic distances, and prevented the ASW LCS from driving into the torpedoes of an enemy submarine. While this modeling issue does mean that an ASW LCS can detect an enemy submarine, it does not provide an unfair advantage due to the modeling work arounds mentioned, and the ASW LCS' inability to deploy an ASW weapon.

The second modeling issue occurs in the MIW scenario with the use of the NLOS missile against enemy mines. Enemy mines are modeled similarly to enemy submarines— as surface contacts with non-MIW capable assets programmed to ignore the mines. In order to prevent the non-MIW capable engaging the mines, the mines were made a non-targetable entity for each SUW weapon system. When running the simulation it was discovered that, while the gunnery systems performed as programmed, the missile systems would occasionally engage the mines if other enemies were detected. In other words, the SUW LCS would not use NLOS to engage detected mines, but if it detected a missile boat and mines were also in range occasionally missiles would engage the mines. After several attempts to trouble shoot the issues with the help of Lloyd Brown, Research Associate with the Simulation Experiments and Efficient Designs (SEED) Center for Data Farming at NPS, the developers of MANA were informed of the issue. The developers responded stating that a possible logic flaw in the MANA code relating to non-targetable classes has been discovered by the MIW scenario used in this thesis. The developers are resolving the issue and will release updates for all MANA versions. (McIntosh, 2008) While this modeling issue does mean that a few mines are engaged with missiles in the MIW scenario, the abstract modeling of the LCS squadron is not compromised due to its low rate of occurrence.

During the model generation phase, the model was reviewed weekly by simulation experts and analysts to ensure the agent behaviors are adequately modeled. The model benefited from inputs from various engineers, military officers, analysts, and



simulation experts through the authors participation in an ASW LCS war game held at Naval Mine and Anti-submarine Warfare Command, San Diego, CA, sponsored by PMS 420 and the 15<sup>th</sup> International Data Farming Workshop held in Singapore, sponsored by the SEED Center for Data Farming at NPS. A preliminary set of runs and analysis of those results was presented to a panel of military officers, analysts, and combat simulators to ensure accuracy. After conducting the preliminary analysis the simulations were run to generate the research data. This process was used to produce accurate scenarios that would yield quality results.

## **6. Summary**

In short, MANA is used to simulate scenarios that may be faced by a LCS squadron. The scenarios cover the specific warfare areas, and are designed to stress the LCS squadron in order to provide insight into its size, composition, and the significance of the technologies involved. The result is a simulation that captures the inherent dangers of operating on the sea and provides insight into how these dangers may be mitigated for a LCS squadron.

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### **III. EXPERIMENTAL DESIGN**

#### **A. INTRODUCTION**

This thesis implements a technique called data farming. Simply stated, data farming uses a simple simulation model that is run numerous times while simultaneously changing the input parameters. (Bain, 2005) The result is an output that covers a large number of possible outcomes. This technique helps provide a better understanding of the system being analyzed and identifies regions that contain interesting events. (Cioppa, Lucas, and Sanchez, 2004) To ensure that the simulation model is searched efficiently, an experimental design is necessary. This chapter begins by discussing the variables used in this thesis, followed by an explanation of the designs used throughout the research. Lastly, the processes of running the experiment are discussed.

#### **B. VARIABLES OF INTEREST**

There are two types of variables commonly used in simulation: controllable and uncontrollable. Controllable variables are those that can be altered by a decision maker in the real world. Uncontrollable variables are those that a decision maker cannot control. Controllable variables are referred to as decision factors, while uncontrollable variables are considered noise factors. This thesis focuses on the decision factors in order to provide greater insight into a new platform. As such, enemy sensor and weapon ranges, as well as their associated probabilities of detection and kill are fixed, making the number of enemies the only enemy variable. Modeling details for each agent and their sensors and weapons is provided in Appendix A. Figure 12 summarizes the variables used, their ranges, and a brief explanation.

<b>Factor</b>	<b>Value Range</b>	<b>Explanation</b>
SUW LCS	1...30	The number of SUW LCS in a given run
ASW LCS	1...30	The number of ASW LCS in a given run
MIW LCS	1...30	The number of MIW LCS in a given run
SUW MH-60R Probability of Detection (PD)	0.5...1.0	Probability of detection associated with the SUW MH-60R sensor
ASW MH-60R Pd	0.5...1.0	Probability of detection associated with the ASW MH-60R sensor
MIW MH-60S	0.5...1.0	Probability of detection associated with the MIW MH-60S sensor
ASW USV Pd	0.5...1.0	Probability of detection associated with the ASW USV
ASW RMV Pd	0.5...1.0	Probability of detection associated with the ASW RMV
MIW USV Pd	0.5...1.0	Probability of detection associated with the MIW USV
MIW RMS Pd	0.5...1.0	Probability of detection associated with the MIW RMS
LCS Pd	0.5...1.0	Probability of detection associated with the LCS Seaframe
NLOS Probability of Kill (Pk)	0.5...1.0	Probability of kill associated with the NLOS Missile System
57mm Pk	0.5...1.0	Probability of kill associated with the 57mm gun system
30mm Pk	0.5...1.0	Probability of kill associated with the 30mm gun system
RAM Pk	0.5...1.0	Probability of kill associated with the RAM point defense system
.50 Caliber Pk	0.5...1.0	Probability of kill associated with the .50 Caliber guns
Blue Torpedo Pk	0.5...1.0	Probability of kill associated with the torpedo used by the ASW MH-60R
Hellfire Pk	0.5...1.0	Probability of kill associated with Hellfire missile system used by the SUW MH-60R
Clearance Pk	0.5...1.0	Probability of kill associated with the mine clearance systems used by the MIW MH-60S
Missile Boats	5...50	Number of missile boats used in a given run
Submarines	5...30	Number of submarines used in a given run
Mines	20...200	Number of agents in an enemy squad
Merchants	0...5	Number of outbound, inbound and anchored merchants used in a given run

Figure 12. Variable factors used in the experimental design. Decision factors are in yellow, and noise factors are in white.

## 1. Controllable Factors

The following variables are chosen in order to explore the effectiveness of the LCS squadron in stressing operational environments. Since a fixed number of systems (i.e., helicopters, USVs, RMVs, and RMSs) come with each type of LCS mission package, only the number of LCS is varied.

***a. SUW LCS***

The number of SUW LCS in the LCS squadron for a given run. For the SUW scenario this is varied from 1 to 30 due to the surface threat being primary. In scenarios where the surface threat is secondary, the number of SUW LCS is varied from 0 to 7.

***b. ASW LCS***

The number of ASW LCS in the LCS squadron for a given run. For the ASW scenario this is varied from 1 to 30 due to the submarine threat being primary. In the SUW scenario, the number of ASW LCS is varied from 0 to 5. ASW LCS are modeled only in the SUW and ASW scenarios.

***c. MIW LCS***

The number of MIW LCS in the LCS squadron for a given run. For the MIW scenario this is varied from 1 to 30 due to the mine threat being primary. MIW LCS are modeled only in the MIW scenario.

***d. SUW MH-60R Probability of Detection (Pd)***

The probability of detection associated with the sensor for the SUW MH-60R. The sensor being modeled is the AN/APS-147 surface search radar. This variable is modeled in all three scenarios.

***e. ASW MH-60R Pd***

The probability of detection associated with the sensor for the ASW MH-60R. The sensor modeled is the AN/AQS-22 dipping sonar. This variable is modeled only in the SUW and ASW scenarios.

***f. MIW MH-60S Pd***

The probability of detection associated with the sensor for the MIW MH-60S. This probability abstractly models the possibility of using two systems for detection. The MIW MH-60S can use either the AN/AQS-20A Mine Hunting System, or

the Airborne Laser Mine Detection Systems (ALMDS), depending on the type of mine. This variable is modeled only in the MIW scenario.

***g. ASW USV Pd***

The probability of detection associated with the sensor used by the USV. This thesis models the use of the Unmanned Dipping Sonar (UDS), which operates similarly to the AN/AQS-22 of the ASW MH-60R. This variable is modeled only in the ASW and SUW scenarios.

***h. ASW RMV Pd***

The probability of detection associated with the sensor used by the ASW RMV. The ASW RMVs operate as a pair, with one using the Remote Towed Active Source (RTAS) and the other using the passive Remote Towed Array (RTA). In this thesis, a single Pd is used for both sensors in each run. This variable is modeled only in the ASW scenario.

***i. MIW USV Pd***

The probability of detection associated with the sensor used by the MIW USV. The sensor modeled is the Mk 104 acoustic device, which is towed by the USV. This variable is modeled only in the MIW scenario.

***j. MIW RMS Pd***

The probability of detection associated with the sensor used by the MIW RMS. The sensor being modeled is the AN/AQS-20A Mine Hunting System, which is towed by the RMS. Unlike the ASW RMVs, the MIW RMSs operate independently. This variable is modeled only in the MIW scenario.

***k. LCS Pd***

The probability of detection associated with the sensor used by the LCS seaframe. The sensor modeled is the 3D surface search radar that will be used by LCS. This variable is modeled in all three scenarios on all types of LCS.

***l. NLOS Probability of Kill (Pk)***

The probability of kill associated with the NLOS missile system used in the SUW mission package. This variable is modeled in all three scenarios.

***m. 57mm Pk***

The probability of kill associated with the 57mm gun system used by the LCS seaframe. This variable is modeled in all three scenarios on all types of LCS.

***n. 30mm Pk***

The probability of kill associated with the 30mm gun systems used in the SUW mission package. This variable is modeled in all three scenarios.

***o. RAM Pk***

The probability of kill associated with the RAM point defense system used by the LCS seaframe. This variable is modeled in all three scenarios on all types of LCS.

***p. .50 Caliber Pk***

The probability of kill associated with the .50 Caliber crew served weapons used by the LCS seaframe. This variable is modeled in all three scenarios but only on the ASW and MIW LCS.

***q. Blue Torpedo Pk***

The probability of kill associated with the Mk 54 torpedo employed by the ASW MH-60R. This variable is modeled only in the SUW and ASW scenarios.

***r. Hellfire Pk***

The probability of kill associated with the Hellfire missile system that is used by the SUW MH-60R. This variable is modeled in all three scenarios.

*s. Clearance Pk*

The probability of kill associated with the clearance capability of the MIW MH-60S. This Pk abstractly models the various methods of mine clearance available to the MH-60S. Three different systems may be used depending on the type of mine: Organic Airborne and Influence Sweep (OASIS), Rapid Airborne Mine Clearance System (RAMICS), and Airborne Mine Neutralization System (AMNS).

**2. Uncontrollable Factors**

The following uncontrollable variables were chosen in order to ensure the scenarios are realistically uncertain and to explore the capabilities of LCS over a range of conditions. As mentioned earlier, these variables are factors that a decision maker is unable to affect and are seen as noise factors.

*a. Missile Boats*

The number of missile boats used in a given run. The number of missile boats is varied from 5 to 50 in the SUW scenario due to their role as the primary threat. They are varied from 0 to 20 in the ASW scenario and from 0 to 15 in the MIW scenario, where they serve as a secondary threat. The missile boats are modeled after the Chinese Fast Attack Craft – Missile (PGGF), and are modeled in all three scenarios.

*b. Submarines*

The number of submarines used in a given run. The number of submarines is varied from 5 to 30 in the ASW scenario due to their role as the primary threat. They are varied from 1 to 5 in the SUW scenario, where they serve as a secondary threat. The submarines are an abstraction of various Kilo class submarines and are modeled only in the SUW and ASW scenarios.

*c. Mines*

The number of mines used in a given run. These mines abstractly model the various types of mines that may be used.



#### ***d. Merchants***

The number of each type of merchant (outbound, inbound, and anchored) used for a given run. The adding of merchants provides realism to the scenarios in that they add to the surface clutter for both friendly and enemy sensors. Neither the enemy nor the LCS squadron is interested in engaging the merchants, but their presence makes detection and classification more difficult. All three types of merchants (outbound, inbound, and anchored) are modeled in both the SUW and ASW scenarios. As such, the number of merchants in each run times the three types of merchants will provide the total number of merchants for that run. Since the MIW scenario only models outbound and inbound merchants, multiplying the number of merchants in each run times the two types of merchants modeled yields the total number of merchants for that run. Merchants are used in the scenarios to provide surface clutter, making detection more difficult for both forces.

### **C. THE EXPERIMENT**

Simulation modeling is an iterative process, which, when done correctly, ensures that the agents and their behaviors are modeled correctly. For this thesis, three stages are used. An initial exploratory design is implemented to gain familiarity with MANA and to debug any modeling issues. Secondly, a preliminary design is created in order to ensure that scenario specific agents are being modeled correctly and to identify any last minute concerns. Lastly, the full experiment is run to obtain the research data. This section explains these three designs in detail, as well as the experimental design tool used to create them.

#### **1. The Nearly Orthogonal Latin Hypercube (NOLH)**

The NOLH experimental design technique was developed at NPS by Lt. Col. Thomas Cioppa, United States Army, in 2002. The technique was designed to efficiently explore simulations that have a large inputs space, requiring minimum a priori assumptions (Cioppa, 2002). The orthogonality of the input variables provides the resulting data statistical properties that allow for efficient analysis. The space filling property of the NOLH allows the analyst to explore more of the input space than the

traditional factorial design in which only high and low values are considered. This is not to say that the use of a NOLH allows the analyst to see all of the input space, but, rather, a larger or more broad section of that input space. A NOLH generation tool created by Professor Susan Sanchez at NPS is used to generate the designs for this thesis. Detailed tables of the experimental designs used are provided in Appendix B. Figure 13 shows the orthogonality and space filling properties of the NOLH through the use of a scatter plot matrix.

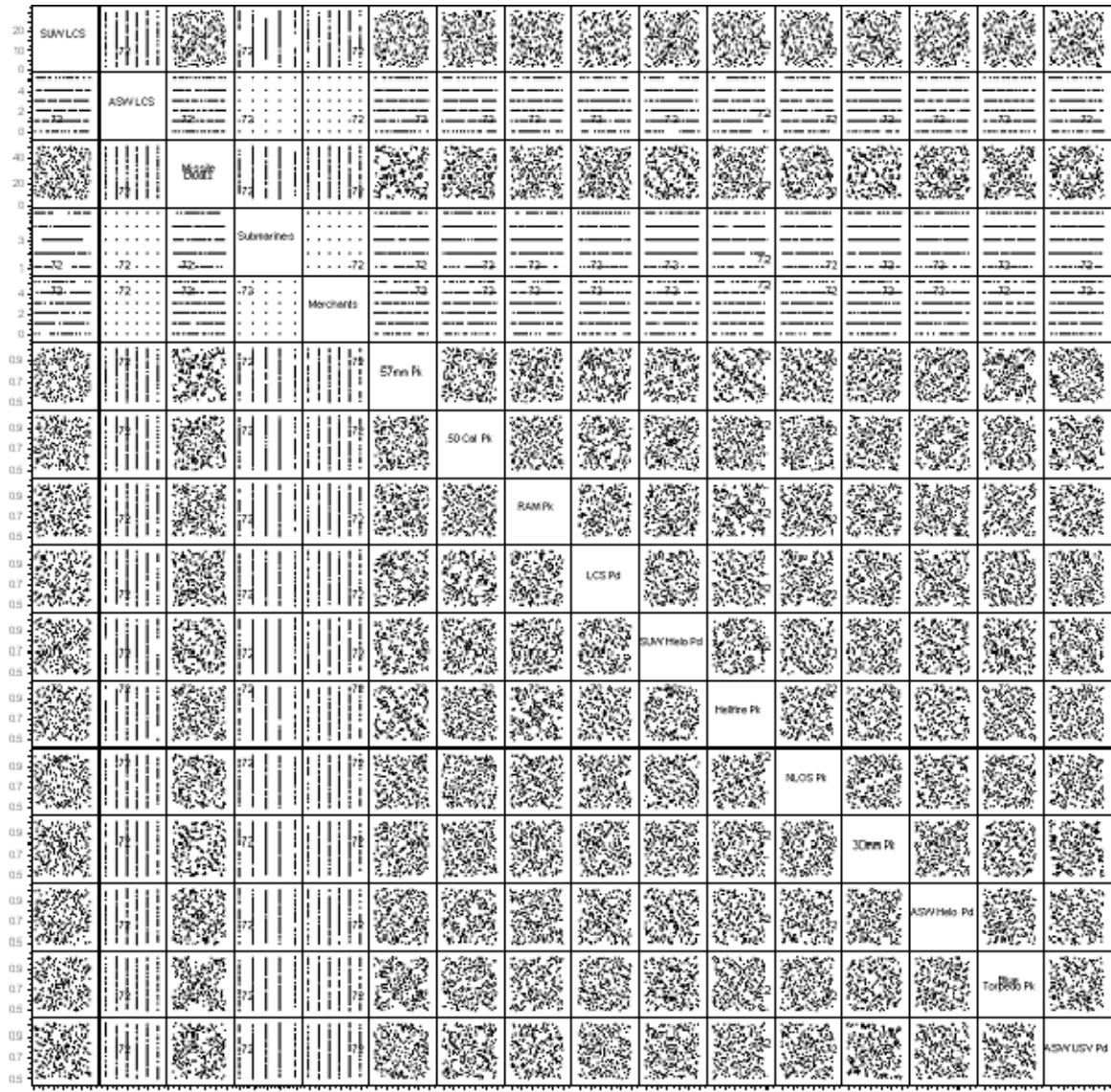


Figure 13. Scatter plot matrix of the variables in the SUW scenario illustrates the orthogonality and space filling properties of the NOLH. Labels on the diagonal are the names of the variables.

## **2. Exploratory Design**

To explore MANA's suitability to address LCS employment, an exploratory design of the SUW scenario was created. This exploratory scenario is very abstract, includes only a primary threat, and is intended to provide insight into the modeling of the different personalities for each agent in the SUW scenario. Four input variables are used: number of LCS, number of missile boats, LCS Pd, and NLOS Pk. These four variables are varied through the NOLH creating 65 different input combinations. Each of these combinations were replicated 100 times, resulting in 6,500 data points. These data points are used to help further develop the simulation model.

## **3. Preliminary Design**

Since the exploratory design is based only on an abstract SUW scenario, additional agents and capabilities are required in order to accurately model the other warfare environments. The preliminary design was created to provide a more detailed look at each scenario after the refinement from the exploratory design. An additional 12 input variables were identified as necessary for the SUW scenario, and 13 variables were added to the ASW and MIW scenarios, resulting in 16 and 17 total input variables respectively. The difference between the number of input variables is due to the use of RMVs and RMSs in the ASW and MIW scenarios. In order to capture as much of the input space as possible, these variables are varied through the NOLH creating 257 different situations for each scenario. These runs were replicated 15 times each, resulting in 3,855 data points per scenario and 11,565 total data points. These data points were analyzed and the results reviewed by simulation experts, analysts, and military officers to ensure that the scenarios were being modeled correctly before conducting the full experiment. Some of the insights provided from these preliminary results include: the addition of the ASW USV in the SUW scenario, and modeling helicopter fuel consumption.

## **4. Full Design**

After refining the simulation model based on the inputs from the preliminary designs, the full design was implemented. Since no additional input variables were

identified, the same 257 runs created by the NOLH for the preliminary design were used. Each of these runs was replicated 30 times each, resulting in 7,710 data points per scenario and 23,130 total data points. These data points were used as the research data the analysis of which is the basis for this thesis and is covered in Chapter IV.

#### **D. RUNNING THE EXPERIMENT**

MANA uses eXtensible Markup Language (XML) files to run simulations. After identifying the input variables and creating the runs through the NOLH, an XML file had to be created for each run. This was accomplished by writing executable programs in a scripting language called Ruby. In short, these programs take the inputs from the NOLH and use them to generate 257 variations of the base XML file for each scenario. The Ruby programs used to convert the inputs of the NOLH into the different XML files are provided in Appendix C. Dave Thomas' *Programming Ruby: The Pragmatic Programmer's Guide* is an excellent source for detailed information on the Ruby programming language.

The subsequent XML files were then placed on a cluster of computers operated by the Simulation Experiments and Efficient Designs (SEED) Center for Data Farming at NPS. This cluster of high performance computers conducted the simulations for both the preliminary and full designs. The preliminary designs took approximately 3 days per scenario to complete while the full designs averaged about 5 days per scenario. These being the case, a total of 34,695 simulated battles were conducted over a period of 24 days. Adding the results of the exploratory design, which simulated 6,500 engagements in 10 hours on a personal laptop, this thesis created 41,195 littoral combat operations in approximately 25 days. The large number of data points emphasizes the analytical strength of the NOLH experimental design.

## **IV. DATA ANALYSIS**

The processes described in the previous chapter generated a large amount of data. This chapter begins by discussing how the data is collected and processed for analysis. The purpose of the analysis is to provide insight into the research questions, which are restated in this chapter. Next, the insights gained are discussed for each scenario. This chapter concludes by providing insights discovered in addition to the research questions.

### **A. DATA COLLECTION AND PROCESSING**

The output provided by MANA is in the form of a comma-separated values (CSV) file that allows for simple processing. This output file provides the number of injuries and casualties for each agent, as well as the total blue force and total red force using MANA's numbering scheme to identify the different agents. Additional information is provided in the output file (i.e., random seed, and run time) that do not contribute directly to the analysis. Due to the large number of output files that required processing, Ruby programs were written to pull the relevant data from the individual output files, label the data appropriately, and combine each of the 257 output files into one large output file per scenario. The Ruby programs used for the processing are provided in Appendix D. The scenario output file contains the results of all 30 replications of each run, resulting in 7,710 rows of data. In order to compile the output data with the 257 rows of input variables, a summary of the scenario output file was needed. This was accomplished by importing the scenario output file into a statistical software package called JMP version 7.0, and calculating the means of each input combination. These 257 rows of mean values were then coupled with the input data to create the summary data set used for analysis. The measures of effectiveness (MOEs) used in this research are mean total Blue casualties and mean total LCS casualties. While mean total Blue casualties encompasses the entire friendly force including helicopters and unmanned vehicles, mean total LCS casualties considers only the number of LCS killed.

## **B. INSIGHTS INTO RESEARCH QUESTIONS**

In Chapter I, three questions were offered as the basis of this research. Each of these questions is addressed through data analysis, and some additional insights have been discovered as well. The research questions for this thesis are:

- How many LCS should there be in an employed squadron?
- What combination of mission packages is needed in the LCS squadron to complete the given focused mission when the possibility of multiple threats exists?
- How effective are sensors and weapon systems with regards to enabling LCS to complete its focused mission?

This analysis includes the use of several analytical tools, including regression trees. Regression trees are exploratory models that help reveal structure in data. Regression trees are particularly useful in summarizing large data sets that contain many variables. (S-PLUS 7, 2005) It is important to note that when viewing a regression tree, the lower values split to the left and higher values split to the right. Appendix E provides a compilation of the graphs and regression results used in conducting this analysis.

### **1. Size and Composition of the Employable LCS Squadron**

The questions regarding the size and composition of the LCS squadron are similar in nature, and, as such, are analyzed together. This section addresses these both of these questions for each of the scenarios.

#### ***a. SUW Scenario***

In order to gain understanding about the relationship between the variables and the MOEs, a regression model for each MOE was conducted using all of the input variables as predictors for the SUW scenario. Figure 14 shows that SUW LCS, ASW LCS, Missile Boats, Submarines, and NLOS Pk are statistically significant, and explain 82 percent of the variance in mean total Blue casualties. These same variables are also statistically significant in predicting mean total LCS casualties, explaining 79 percent of

the variance in that MOE. This analysis reveals that submarines and SUW LCS are the dominant factors in the SUW scenario. Having established the significant factors for the two MOEs, regression tree analysis is used to determine possible thresholds.

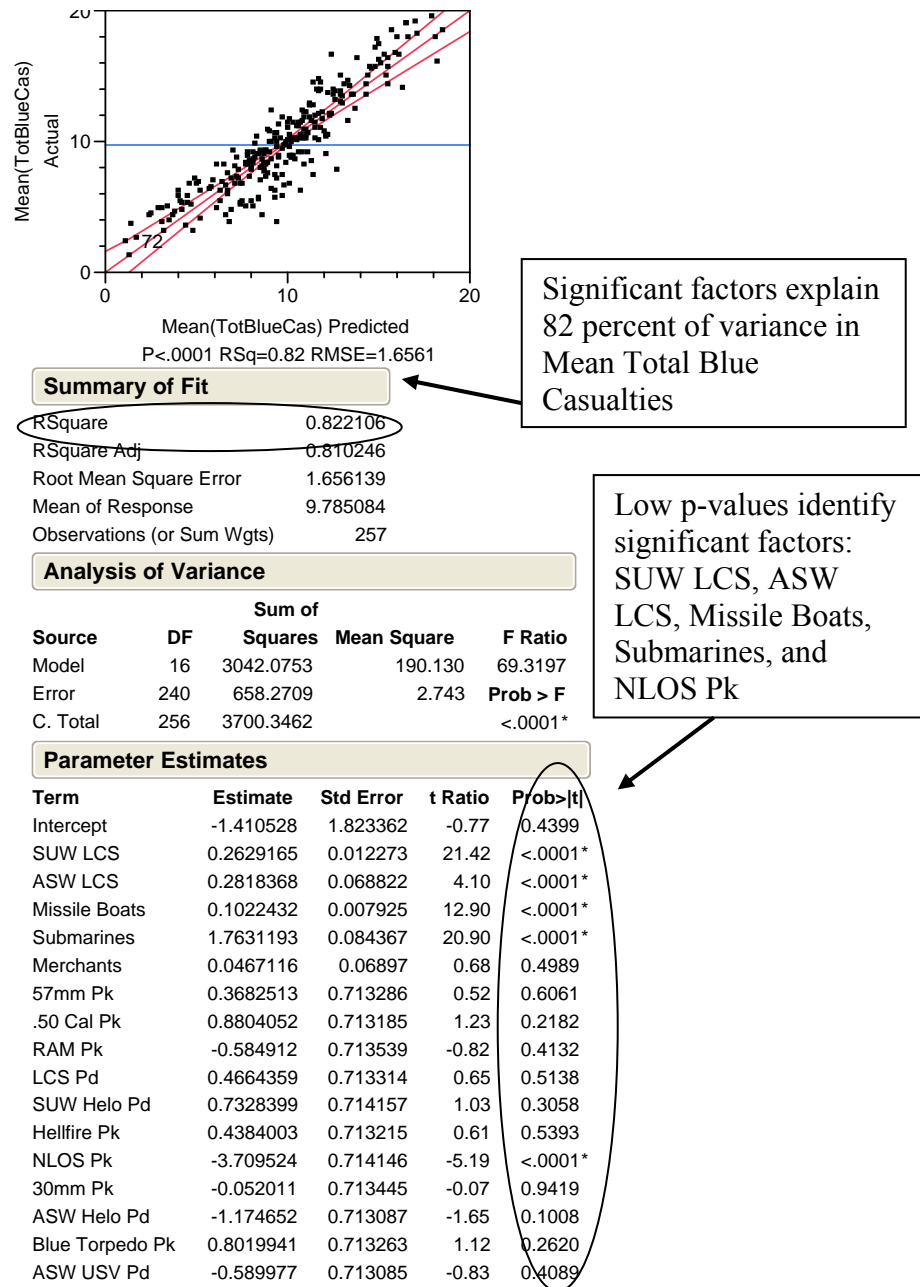


Figure 14. Regression analysis of Mean Total Blue Casualties for the SUW scenario

Regression analysis not only illustrates percent of the variation explained and the significant factors, but identifies which factors have more influence and what their contribution to the MOE is. In the case of Figure 14, number of SUW LCS and number of submarines are the most influential factors on mean total Blue casualties, which is quantified by their t-ratios—the larger the t-ratio the more influential the factor. The estimate column of the regression analysis shows the contribution of each factor to the MOE. For example, for each submarine added to the engagement, mean total Blue casualties will increase by 1.763. Estimates with negative values will decrease the MOE.

Regression tree analysis of mean total Blue casualties shows that the presence of submarines has a significant impact. It also suggests that when there are less than three submarines, having less than ten SUW LCS produces lower mean total Blue casualties. When considering situations where there are three or more submarines, less than five SUW LCS and two ASW LCS produces lower mean total Blue casualties. From this initial look, the limit of ten SUW LCS was considered an upper bound for the LCS squadron and the combination of less than five SUW LCS and two ASW LCS considered the lower bound. This provides a range of six to ten LCS for the employable squadron. Figures 15 and 16 show portions of the regression tree for mean total Blue casualties that illustrate the analysis for the lower and upper bounds of six and ten. The full regression tree is provided in Appendix E.



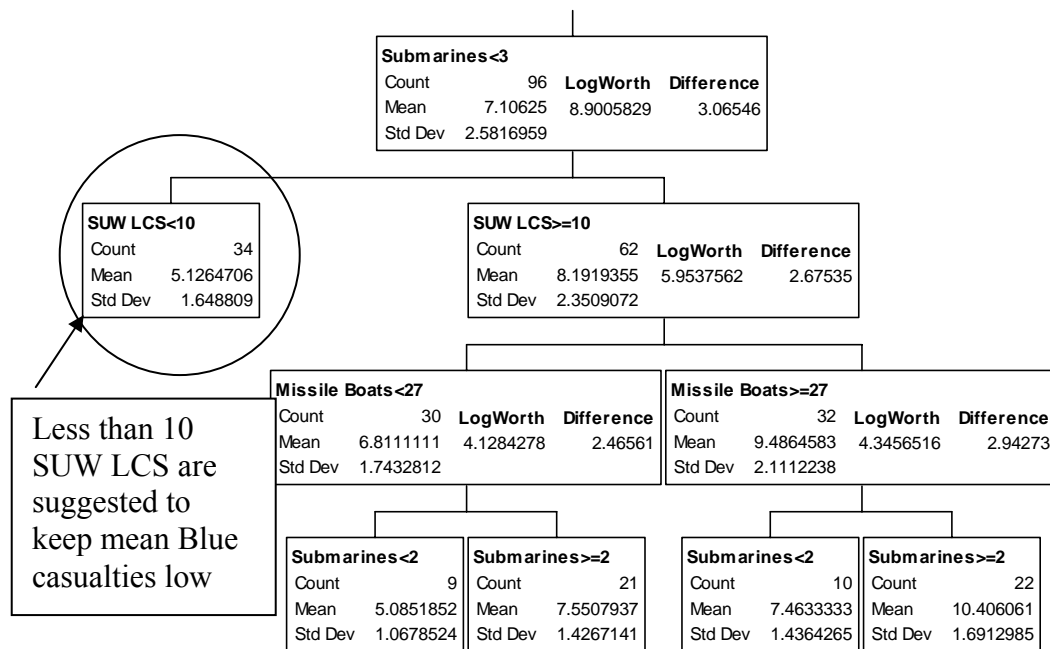


Figure 15. Portion of regression tree of mean total Blue casualties where submarines are less than three

As mentioned earlier, regression tree analysis conducts a binary split with the lower values displayed on the left hand side. In each split the regression tree shows how many cases meet the specified criteria, the mean of the MOE for these cases, as well as the standard deviation. Also included in the regression tree analysis is the significance of the split, captured by the log worth value. For example, in Figure 15 the first split is on having less than three submarines. There are 96 situations meeting this criteria, and for these 96 situations 7.10 is the average number of Blue casualties with a standard deviation of 2.58. The log worth of this split is higher than the other splits showing its significance.

Regression tree analysis of mean total LCS casualties produced similar results, supporting the squadron size of six to ten LCS (Appendix E). Since both of these trees considered SUW LCS and ASW LCS separately, a new column of data was created labeled Total LCS; its values being the sum of the LCS used in each run. Regression tree analysis of mean total LCS casualties when considering Total LCS shows that six to ten LCS produces lower mean total LCS casualties, including in situations where there are

greater than three submarines. Similar analysis of mean total Blue casualties suggests that having less than eight total LCS produces lower mean casualties in general, but that having eight or more total LCS produces lower mean casualties in situations where there are less than three submarines and less than 20 missile boats. This suggest that a squadron of six to ten LCS is capable of producing lower mean total Blue casualties and mean total LCS casualties even in situations where there are up to three submarines and 20 missile boats.

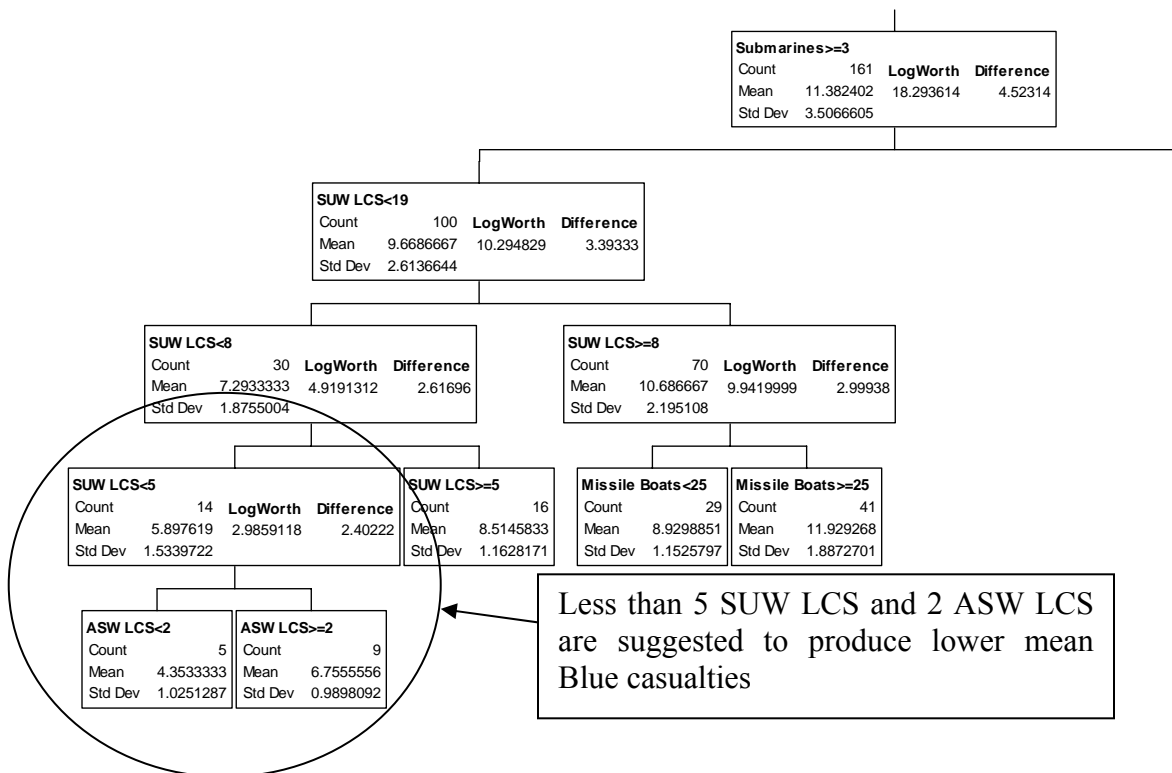


Figure 16. Portion of regression tree for mean total Blue casualties where there are three or more submarines

In Figure 17, plotting mean total Blue casualties versus total LCS shows that mean total Blue casualties do increase over the range of six to ten, but at a slower rate. In these charts, each dot represents the mean of 30 simulated littoral combat operations in which 17 different parameters have been varied. The line connects the mean value of the y-axis, either mean total Blue casualties or mean total Red casualties,

for the corresponding number of total LCS. These graphs are used to identify significant trends or knees in the curve. Comparing this to the mean total Red casualties for the same range reveals that six to ten LCS produce up to 4.7 times more mean Red casualties than mean LCS casualties. There is a noticeable plateau, however, in the mean total Blue casualties graph suggesting stable, non-increasing casualties over the 10 – 13 LCS range. When considering this plateau in the mean total Blue casualties in terms of mean total Red casualties, it was discovered that this range produces up to 3.5 times as many Red casualties. This lower rate of mean Red casualties combined with higher, although stable, mean total Blue casualties further supports the effectiveness of a squadron comprised of six to ten LCS.

Having addressed the size of the LCS squadron for the SUW scenario, consideration is given for the composition. Previous regression tree analysis has consistently suggested that less than five SUW LCS and two ASW LCS produces lower mean casualties for both the Blue Force and LCS proper. In order to capture how the Red forces fares in the situation, regression tree analysis of mean total Red casualties was conducted. This analysis suggests that at least five SUW LCS should be included in the squadron, as this produces higher mean Red casualties. With a size of six to ten LCS and a composition of at least five SUW LCS and two ASW LCS, an employable LCS squadron is able to produce high mean Red casualties while keeping mean Blue and LCS casualties low.

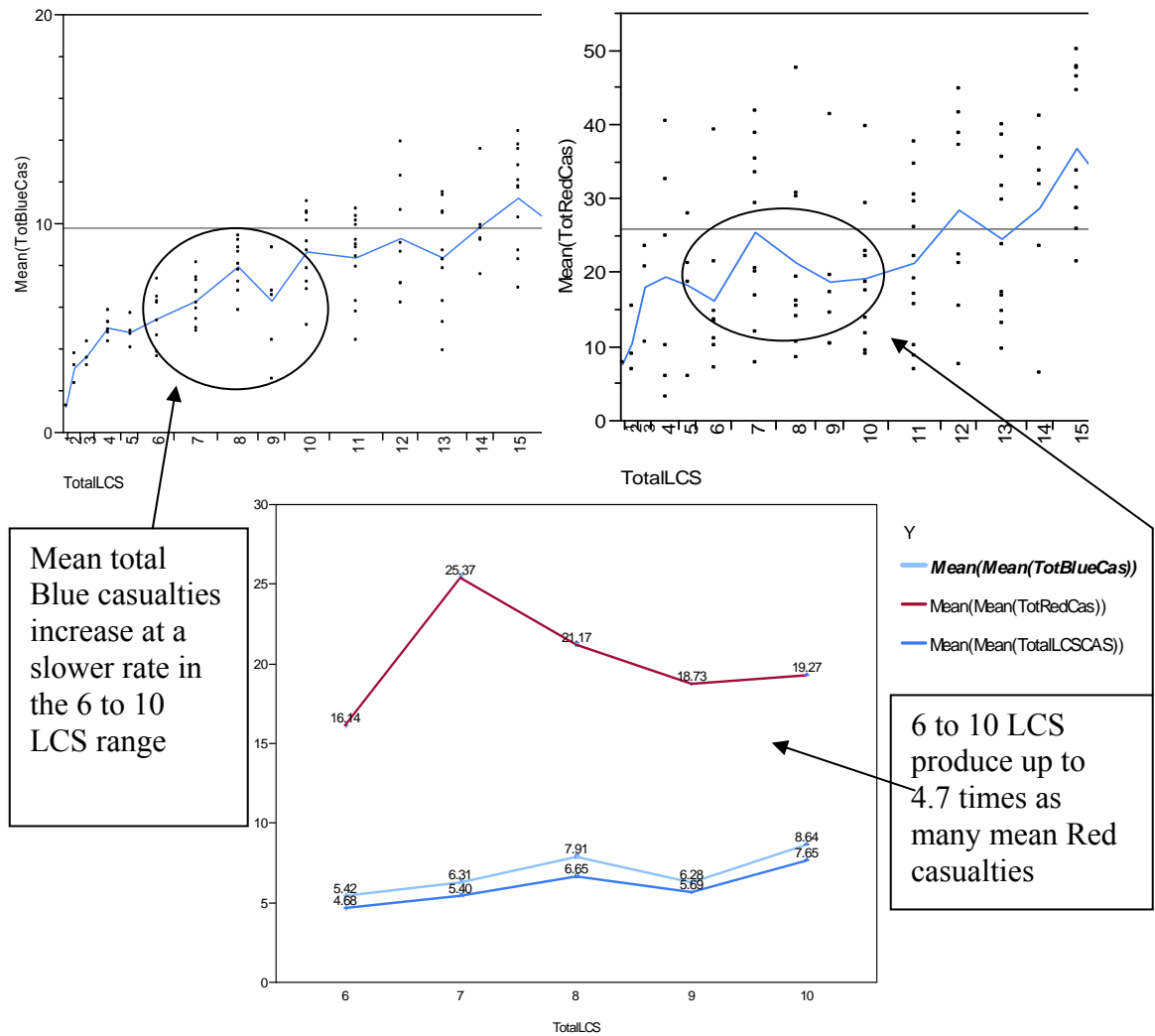


Figure 17. Graphs of Mean Total Blue Casualties, and Mean Total Red Casualties illustrating the impact of an employable LCS squadron containing six to ten LCS

### b. ASW Scenario

Analysis of the ASW scenario was conducted in a similar fashion. A linear regression was performed in order to provide understanding of the relationship between the MOEs and the variables. Regression analysis reveals that ASW LCS, missile boats, and submarines are statistically significant in predicting mean total Blue casualties and that these parameters explain 78 percent of the variation in that MOE. The analysis also shows that submarines, ASW LCS, and SUW LCS are the dominant factors in the ASW scenario. Figure 18 shows the regression analysis of mean total Blue

casualties for the ASW scenario. The difference between the ASW scenario and the SUW scenario is the use of all the unmanned vehicles in the ASW mission package. This increase in number of Blue forces increases the ASW LCS contribution to mean total Blue casualties. When analyzing mean total LCS casualties, ASW LCS, SUW LCS, missile boats, submarines, and NLOS Pk are identified as statistically significant and explain 73 percent of the variance in that MOE. While the number of SUW LCS does not seem to be significant in predicting mean total Blue casualties, it does contribute in determining mean total LCS casualties.

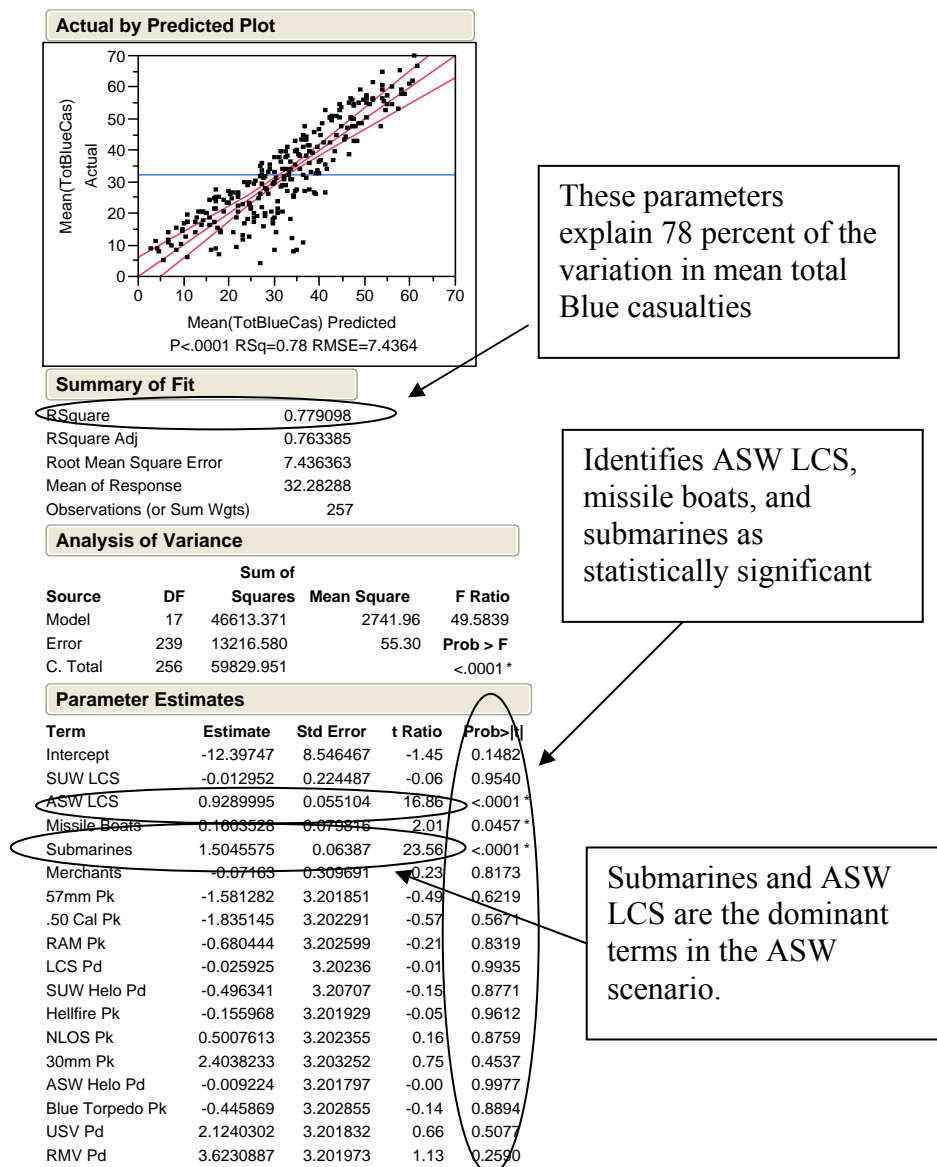


Figure 18. Regression analysis of mean total Blue casualties for the ASW scenario.

Having identified the significant factors among the ASW scenario data set, regression tree analysis was conducted. The use of the Total LCS data column was also implemented for this data set. Regression tree analysis of mean total Blue casualties shows that submarines are the most significant factor, a trait shared with the SUW scenario. When there are 11 to 16 submarines, the regression tree suggests that less than 11 total LCS produces lower mean Blue casualties, which supports the recommended upper bound of ten LCS per squadron. The regression tree also suggests that five ASW LCS produce lower mean Blue casualties in situations where there are less than 11 submarines and when there are 16 or more submarines. This disparity, suggesting the same number for both high and low numbers of enemies, suggests that there may be a limit to the number of submarines a squadron of LCS can handle. Regression tree analysis of mean total LCS casualties further displays the disparity by suggesting 24 or more total LCS are needed to lower mean LCS casualties when there are less than 14 submarines, and that less than 8 total LCS are necessary to lower mean LCS casualties when there are 18 or more submarines. This recommendation of either saturation or minimal involvement further emphasizes that there may be an upper bound for the amount of submarines an LCS squadron can handle. Figure 19 shows a portion of the regression tree for mean total LCS casualties, which suggests that ten submarines may be the most an LCS squadron can combat without support. The full regression tree can be found in Appendix E.

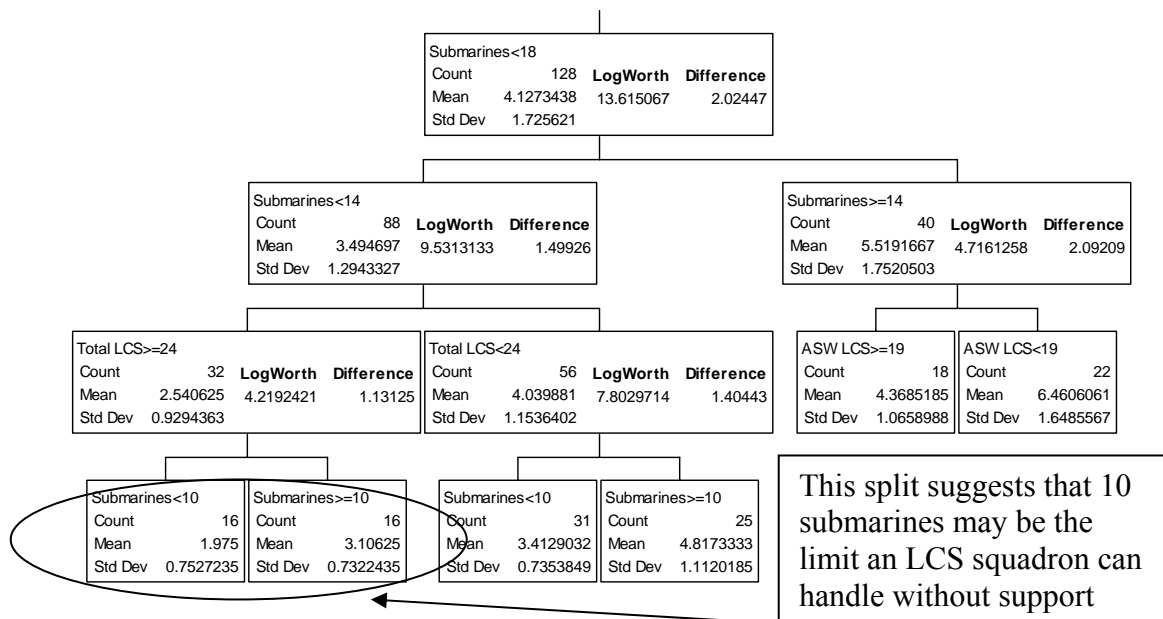


Figure 19. Portion of regression tree for mean total LCS casualties for the ASW scenario

Figure 20 illustrates the impact of an employed LCS squadron with six to ten LCS in the ASW scenario. Mean total Blue casualties steadily increase over the range of six to ten LCS, due to the increase in the number of unmanned vehicles. Plotting mean total LCS casualties versus total LCS shows that the six to ten LCS range provides the knee in the curve. While mean LCS casualties are increasing, they are increasing at a slower rate right before they spike. Similarly, there is an increase in mean Red casualties over the six to ten LCS range. This supports the previous analysis in the SUW scenario suggesting a squadron size of six to ten LCS.

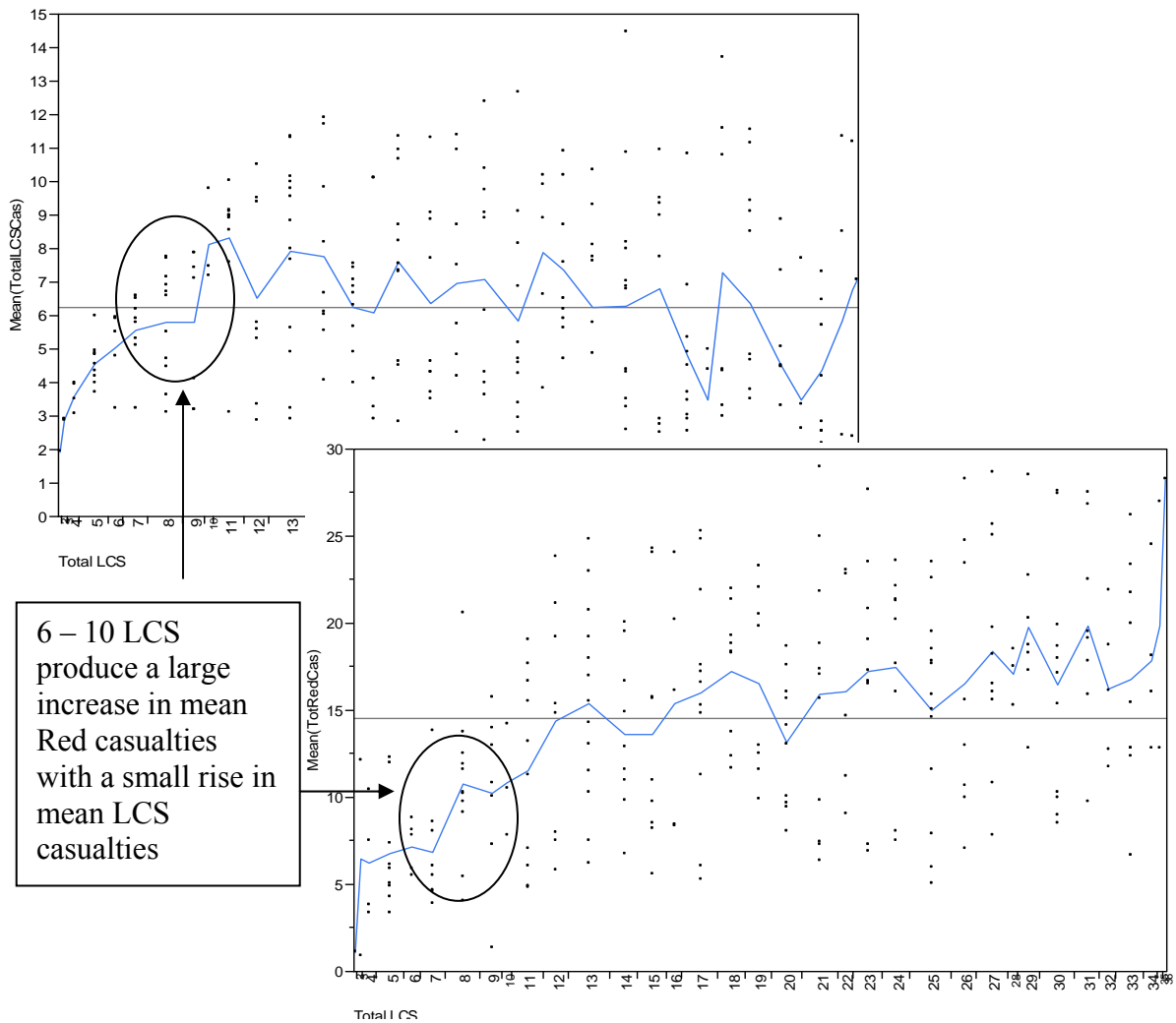


Figure 20. Graphs of mean total LCS casualties versus total LCS and mean total Red casualties versus total LCS

In considering the squadron's composition for the ASW scenario, previous regression tree analysis suggested five ASW LCS in order to provide lower mean Blue casualties. Adding one SUW LCS increases mean total LCS casualties but produces an increase in mean Red casualties 1.5 times larger. To determine the number of LCS that would cause the largest number of Red casualties, regression tree analysis of mean Red casualties was conducted. The regression tree shows that seven or more ASW LCS produces higher mean Red casualties. When one SUW LCS is added to the seven ASW LCS it produces the largest increase in mean Red casualties in the six to ten LCS range.



This suggests that while at least five ASW LCS and one SUW LCS is the recommended squadron composition to produce lower mean Blue casualties in the ASW scenario, seven ASW LCS and one SUW LCS provides the highest mean Red casualties.

*c. MIW Scenario*

The MIW scenario differs from the other scenarios in that it is the only scenario that does not include submarines. While this may not be the only factor, it may contribute to the significantly lower LCS casualties seen in the MIW scenario; mean total LCS casualties do not exceed 0.1 throughout the range of simulations. Similar to the ASW scenario, however, unmanned vehicles in the MIW scenario suffer larger casualties than the LCS. This being the case, mean total Blue casualties plays a more significant role as a MOE in the MIW scenario. Regression analysis of mean total Blue casualties identifies MIW LCS, SUW LCS, missile boats, mines, and clearance Pk as statistically significant, and shows that these parameters explain 78 percent of the variation in that MOE. Similar analysis for mean total LCS casualties identifies MIW LCS, missile boats, mines, and 57mm Pk as statistically significant, but these parameters only explain 15 percent of the variation for that MOE. Again, this is due to the low mean LCS casualties seen in the MIW scenario. Regression analysis also shows that mines, missile boats, and MIW LCS are the dominant factors. Figure 21 shows the regression analysis of mean total Blue casualties for the MIW scenario.

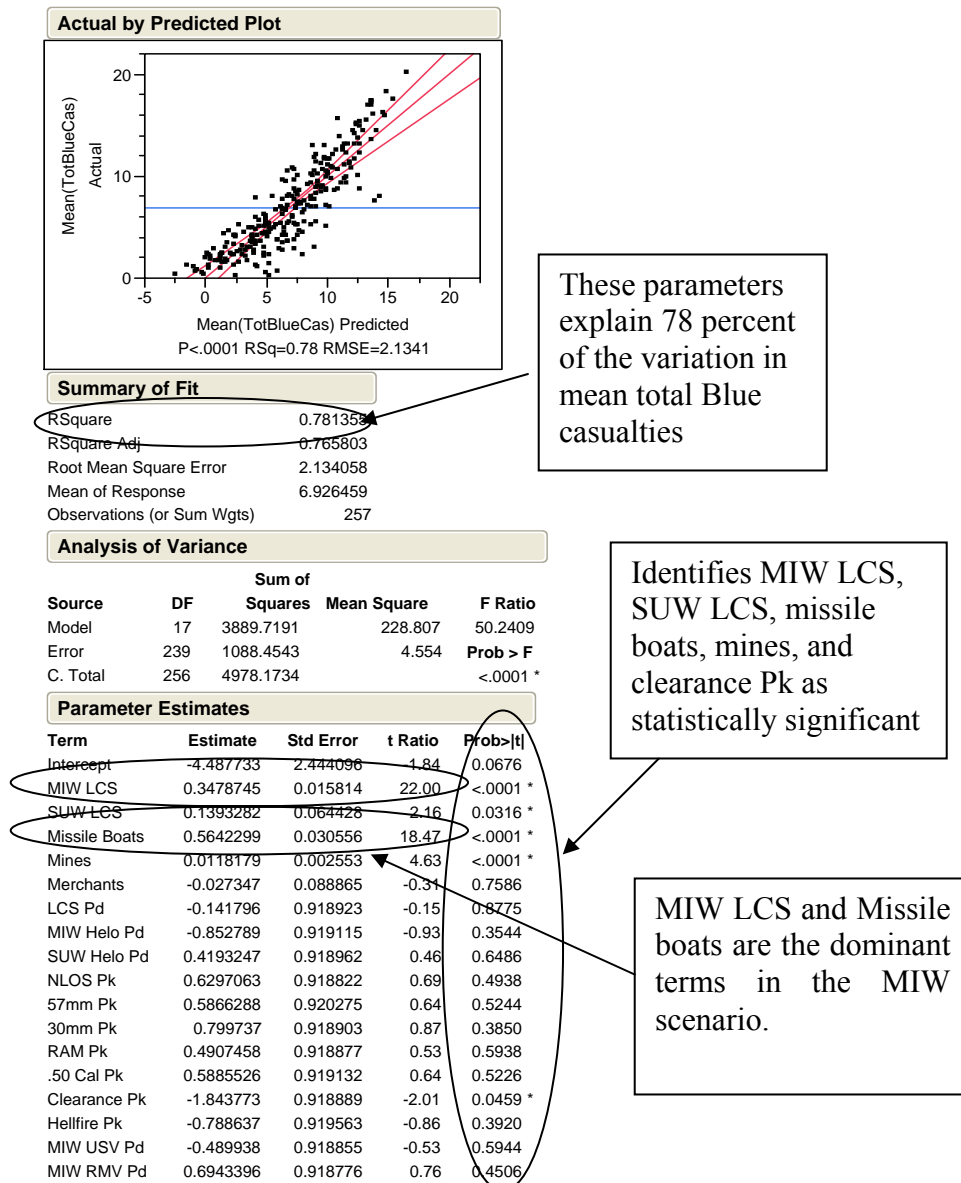


Figure 21. Regression analysis of mean total Blue casualties for the MIW scenario

With both the SUW and ASW scenarios supporting a squadron of six to ten LCS, regression tree analysis was conducted to determine what thresholds would be discovered in the MIW scenario. Similar to the other scenarios, the Total LCS column of data was used in this analysis. The regression tree for mean total Blue casualties suggests that less than 12 MIW LCS produces lower mean Blue casualties. It further suggests that six or more MIW LCS produces lower mean Blue casualties when there are up to eight

missile boats guarding the mine field. This is significant since the regression tree also shows that the missile boats guarding the mine field have a greater impact on Blue casualties than the mines themselves. Regression tree analysis of mean total LCS casualties suggests that mines do play a significant role in LCS casualties with less than 182 mines producing lower mean LCS casualties. In situations where there are less than 182 mines, six or more MIW LCS produce lower mean LCS casualties, which are further lowered by adding one or more SUW LCS. This supports previous analysis of a squadron size of six to ten LCS. Figure 22 shows a portion of the regression tree of mean total Blue casualties for the MIW scenario. The full regression tree is provided in Appendix E.

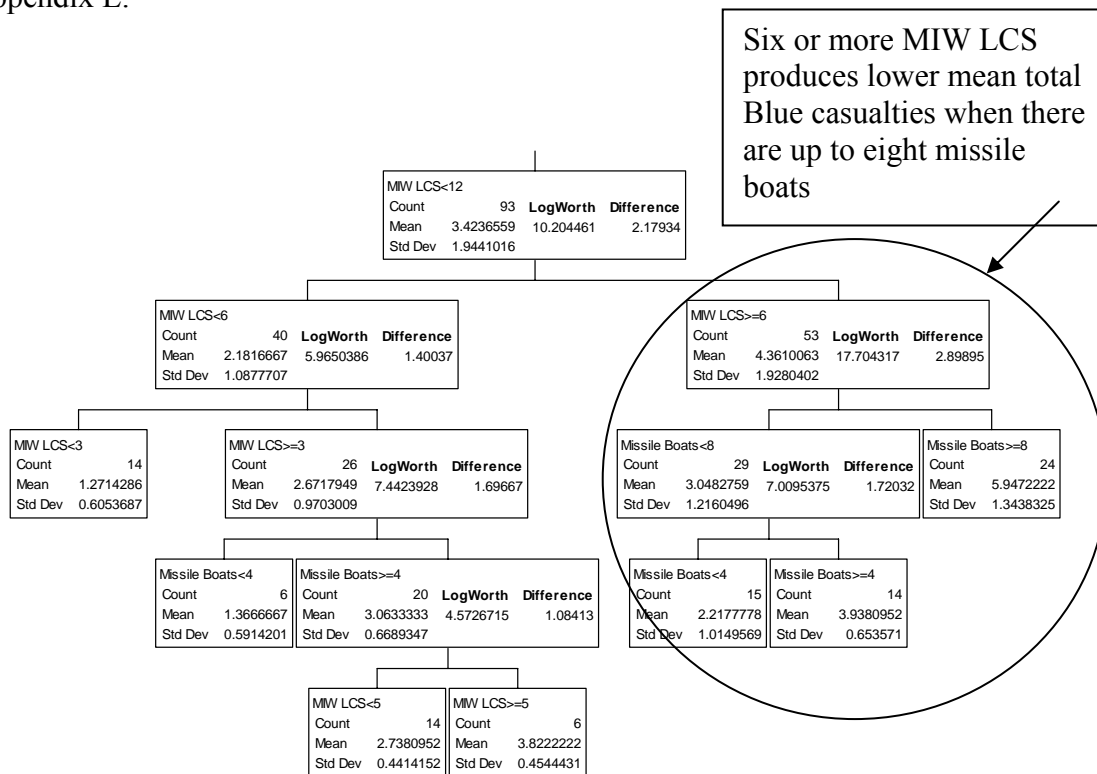


Figure 22. Portion of regression tree for mean total Blue casualties for the MIW scenario

Plotting mean total Blue casualties versus total LCS shows that mean Blue casualties do increase in the six to ten LCS range, but also shows that use of more than ten LCS causes a significant and steady increase in mean Blue casualties. Comparing

this to mean total Red casualties versus total LCS reveals a significant increase in mean Red casualties in the range of six to ten LCS range, with no increase in mean Red casualties when more than ten LCS are used. These results further support a squadron size of six to ten LCS. Figure 23 shows the impact of an employed squadron with six to ten LCS in the MIW scenario.

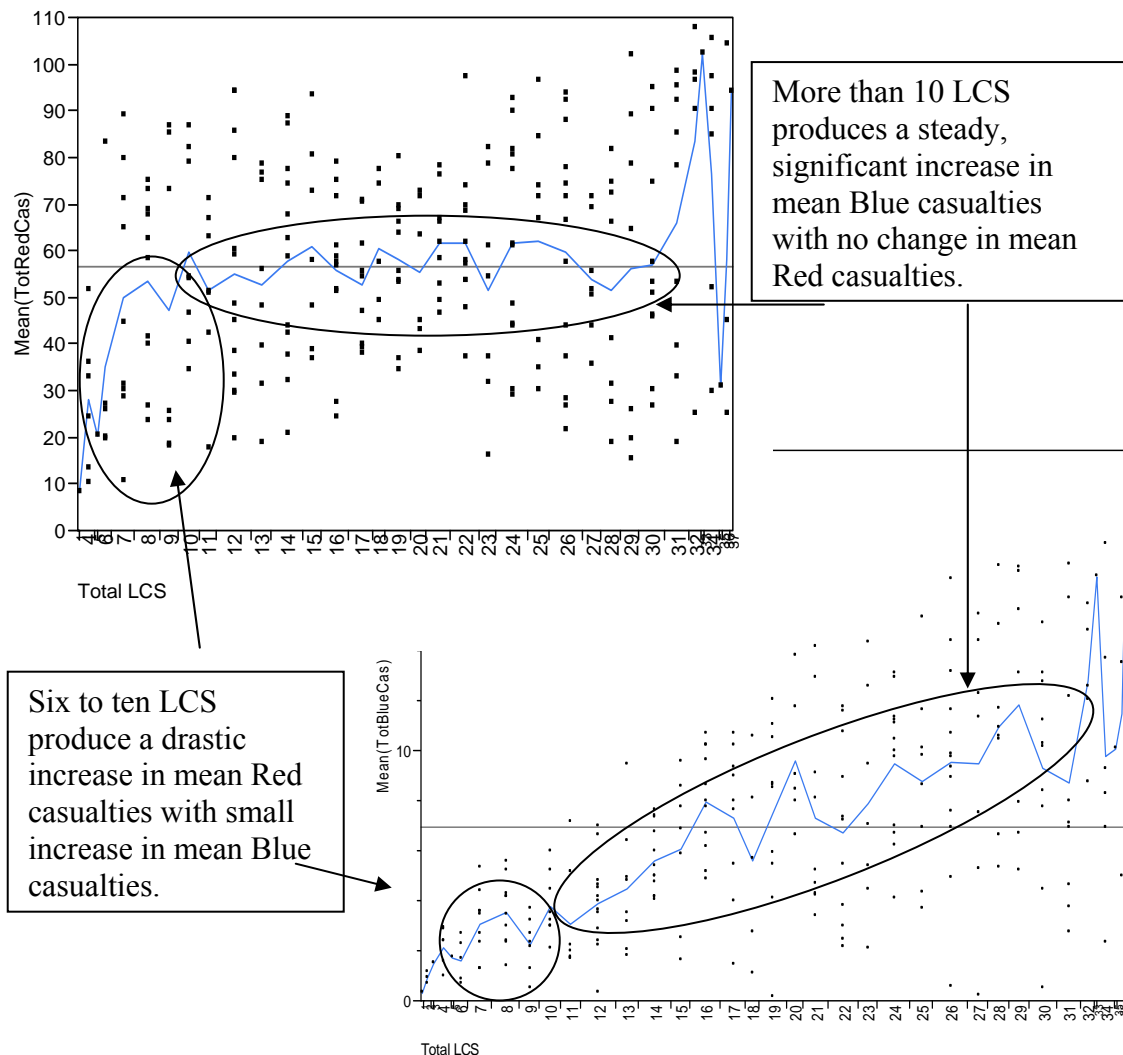


Figure 23. Graphs of mean total Red casualties versus total LCS and mean total Blue casualties versus total LCS

Previous regression tree analysis suggests six MIW LCS and one SUW LCS as the composition of the employable squadron in the MIW scenario. With LCS

casualties being low and the related analysis explaining little of the variance in mean total LCS casualties, analysis of mean Red casualties was conducted to help determine the squadron's composition. Regression analysis identifies MIW LCS, SUW LCS, missile boats, mines, and clearance Pk as statistically significant in predicting mean Red casualties, and shows that these parameters explain 92 percent of the variation in mean Red casualties. More specifically, regression tree analysis suggests that using one or more SUW LCS produces higher mean Red casualties in situations when there are 96 to 140 mines in the mine field. If the enemy deploys 141 mines or more, however, using two or more SUW LCS would produce higher mean Red casualties. This is due to using more missile boats to protect a larger minefield, and would not apply if only the number of mines were increased. The analysis of the MIW scenario shows that a composition of at least six MIW LCS and one or more SUW LCS will produce low mean Blue casualties while inflicting high mean Red casualties.

***d. Summary***

In summary, all three scenarios provide analytic support for an employed LCS squadron that consists of six to ten LCS. A composition of at least five SUW LCS and two ASW LCS is recommended for the SUW scenario, while at least five ASW LCS and one SUW LCS is recommended for the ASW scenario. In the MIW scenario, at least six MIW LCS and one or more SUW LCS produced low mean Blue casualties and high mean Red casualties.

**2. Effects of Sensors and Weapon Systems**

The third question driving this research seeks insight into the contribution of sensors and weapon systems to the effectiveness of LCS. Sensors and weapon systems are necessary in combat; the focus of this question, however, is how significant they are with respect to the MOEs. This section discusses the significance of sensors and weapon systems in each of the scenarios.

*a. SUW Scenario*

Analysis of the effect of sensors and weapon systems is conducted similar to that of determining the size and composition of the employable squadron. The first step is to understand the relationship between the variables and the MOEs. For sensors and weapon systems, the parameters used in the regression analysis are only the variables that are probabilities. This is done in order to gain insight into the contribution of sensors and weapon systems alone. In the SUW scenario, for example, regression analysis identified NLOS Pk as statistically significant in predicting both mean total Blue casualties and mean total LCS casualties when in the presence of SUW LCS, ASW LCS, missile boats, and submarines. Regression analysis of both MOEs, when considering only sensors and weapon systems, does not identify any of them as statistically significant. The fact that NLOS Pk is not statistically significant when only sensors and weapon systems were considered suggests that its contribution is reliant on one of the other parameters. This is further supported by its lack of presence in the previous regression tree analysis when determining size and composition of the employable squadron. Effects screening analysis was conducted for each MOE to determine when sensors and weapon systems do become statistically significant. This analysis suggests that sensors and weapon systems become statistically significant only in the interaction terms. This demonstrates the interdependence that can exist between sensors and the weapon systems that are used to neutralize targets they detect.

A subset of the data was created where total LCS ranged from six to ten in order to determine if sensors and weapon systems become significant over this range. The analysis, however, produced the same results with the sensors and weapon systems becoming statistically significant only in the interaction terms. The lack of statistical significance among any of the sensors or weapon systems in predicting the MOEs suggests that numbers of LCS has a greater impact than sensors and weapon systems in the SUW scenario. Figure 24 shows the regression analysis of mean total Blue casualties and mean total LCS casualties when considering only sensors and weapon systems for the SUW scenario.

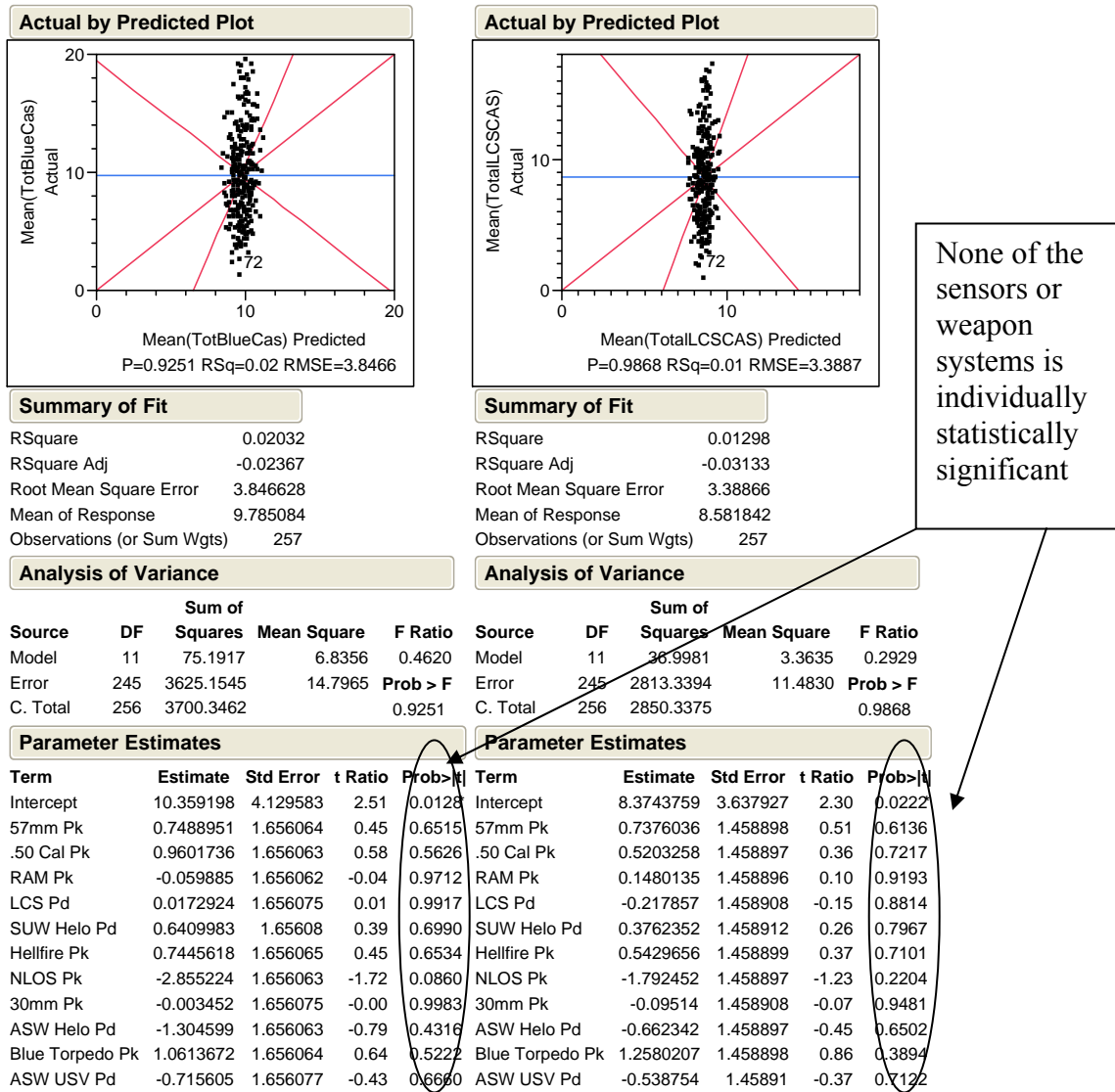


Figure 24. Regression analysis of mean total Blue casualties and mean total LCS casualties when considering only sensors and weapon systems for the SUW scenario

### b. ASW Scenario

As with the SUW scenario, the previous analysis of the ASW scenario identified sensors and weapon systems as statistically significant in the presence of other parameters; LCS Pd in predicting mean total Blue casualties and blue torpedo Pk in predicting mean total Red casualties. Neither of these systems is statistically significant, however, when only sensors and weapon systems are considered. When regressing

against both the full data set and the subset of data where total LCS is from six to ten, none of the sensors or weapon systems are identified to be statistically significant in predicting the MOEs. While effects screening analysis of the full data set reveals significance in only the interaction terms, effect screening of the data subset shows statistical significance among individual sensors and weapon systems. When analyzing mean total Blue casualties, effects screening identifies Hellfire Pk, RAM Pk, SUW MH-60R Pd, and other interaction terms as statistically significant, and that they explain 51 percent of the variation in that MOE. Similarly, effects screening analysis of mean total Red casualties identifies ASW USV Pd and other interaction terms as statistically significant and that they explain 54 percent of the variation in mean Red casualties. Regression tree analysis was used to determine possible thresholds, but was complicated by the interaction terms. Previous regression tree analysis, however, suggests that a blue torpedo Pk of 79 percent or more produces higher mean Red casualties when there are seven or more ASW LCS in the squadron and 15 or more missile boats. These results show that in a squadron size of six to ten LCS, Hellfire Pk, RAM Pk, SUW MH-60R Pd, and ASW USV Pd significantly contribute to the MOEs, and that a blue torpedo Pk of at least 79 percent produces high mean Red casualties in certain situations. Figure 25 shows the regression analysis resulting from the effects screening for mean total Blue casualties over the data subset in the ASW scenario when considering only at sensors and weapon systems.



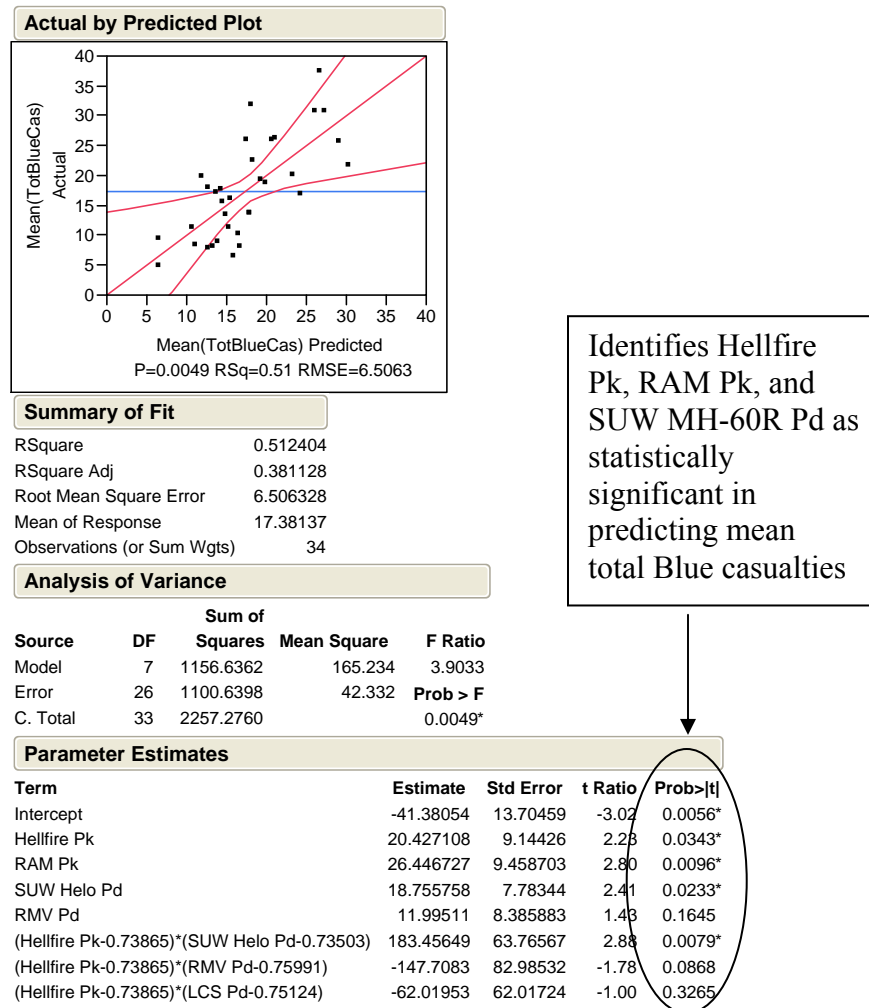
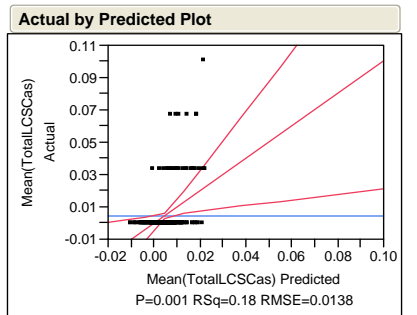


Figure 25. Regression analysis resulting from effects screening of mean total Blue casualties in the ASW scenario when considering only sensors and weapon systems

### c. *MIW Scenario*

Once again, previous regression analysis has identified certain sensors and weapon systems as statistically significant in the presence of other parameters; clearance Pk in predicting mean total Blue casualties and 57mm Pk in predicting mean total LCS casualties. These two weapon systems, as well as the other sensors and weapon systems, fail to be identified as statistically significant, however, when only sensors and weapon systems are considered. These results hold true for both the full data set and the subset of data where total LCS is from six to ten. Effects screening analysis of the full data set

identifies 57mm Pk and other interaction terms as statistically significant in predicting mean total LCS casualties and shows that these parameters explain only 18 percent of the variation in the MOE. Effects screening analysis of the six to ten total LCS subset shows statistical significance for sensors and weapon systems only in the interaction terms. While regression tree analysis was unable to identify thresholds for the sensors and weapon systems identified as statistically significant, these results show that 57mm Pk significantly contributes to mean total LCS casualties. It is significant to note that the 57mm is the predominant weapon on a MIW LCS for surface warfare. Figure 26 shows the regression analysis resulting from effects screening of mean total LCS casualties when considering only at sensors and weapon systems for the MIW scenario.



Summary of Fit	
RSquare	0.179159
RSquare Adj	0.101986
Root Mean Square Error	0.013814
Mean of Response	0.004669
Observations (or Sum Wgts)	257

Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	22	0.00974569	0.000443	2.3215
Error	234	0.04465120	0.000191	
C. Total	256	0.05439689		
				Prob > F
				0.0010 *

Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.0262459	0.007131	3.68	0.0003 *
57mm Pk	-0.023588	0.00925	-2.55	0.0114 *
(57mm Pk-0.75001)*(Clearance Pk-0.75001)	0.0409345	0.041786	0.98	0.3283
(LCS Pd-0.75001)*(LCS Pd-0.75001)	-0.062204	0.046226	-1.35	0.1797
(MIW RMV Pd-0.75001)*(NLOS Pk-0.75001)	-0.078522	0.044551	-1.76	0.0793
(57mm Pk-0.75001)*(MIW Helo Pd-0.75001)	-0.069605	0.039183	-1.78	0.0770
(MIW Helo Pd-0.75001)*(MIW Helo Pd-0.75001)	-0.121427	0.047282	-2.57	0.0108 *
(LCS Pd-0.75001)*(LCS Pd-0.75001)*(LCS Pd-0.75001)	-0.011152	0.149875	-0.07	0.9407
(57mm Pk-0.75001)*(Clearance Pk-0.75001)*(Hellfire Pk-0.75001)	0.6922165	0.299527	2.31	0.0217 *
(Clearance Pk-0.75001)*(Clearance Pk-0.75001)*(Hellfire Pk-0.75001)	0.7708877	0.282034	2.73	0.0067 *
(MIW USV Pd-0.75001)*(MIW USV Pd-0.75001)*(Hellfire Pk-0.75001)	-0.912387	0.294377	-3.10	0.0022 *
(57mm Pk-0.75001)*(SUW Helo Pd-0.75001)*(Hellfire Pk-0.75001)	0.1087525	0.327118	0.33	0.7398
(57mm Pk-0.75001)*(Hellfire Pk-0.75001)*(Hellfire Pk-0.75001)	0.5126974	0.344301	1.49	0.1378
(SUW Helo Pd-0.75001)*(Hellfire Pk-0.75001)*(Hellfire Pk-0.75001)	-0.31323	0.207813	-1.51	0.1331
(57mm Pk-0.75001)*(MIW USV Pd-0.75001)*(MIW RMV Pd-0.75001)	-0.289383	0.319865	-0.90	0.3666
(MIW USV Pd-0.75001)*(MIW RMV Pd-0.75001)*(MIW RMV Pd-0.75001)	-0.395988	0.215892	-1.83	0.0679
(57mm Pk-0.75001)*(57mm Pk-0.75001)*(NLOS Pk-0.75001)	-0.182096	0.311509	-0.58	0.5594
(MIW USV Pd-0.75001)*(MIW USV Pd-0.75001)*(NLOS Pk-0.75001)	-0.496276	0.265644	-1.87	0.0630
(MIW USV Pd-0.75001)*(SUW Helo Pd-0.75001)*(NLOS Pk-0.75001)	-0.54054	0.359677	-1.50	0.1342
(Hellfire Pk-0.75001)*(Hellfire Pk-0.75001)*(NLOS Pk-0.75001)	0.3605902	0.29942	1.20	0.2297
(Clearance Pk-0.75001)*(Clearance Pk-0.75001)*(MIW USV Pd-0.75001)*(SUW Helo Pd-0.75001)	-0.428785	1.570634	-0.27	0.7851
(57mm Pk-0.75001)*(57mm Pk-0.75001)*(SUW Helo Pd-0.75001)*(Hellfire Pk-0.75001)	0.8868304	1.623743	0.55	0.5855
(57mm Pk-0.75001)*(Clearance Pk-0.75001)*(Clearance Pk-0.75001)*(MIW RMV Pd-0.75001)	1.8909118	1.459144	1.30	0.1963

Identifies 57mm Pk and other interaction terms as statistically significant when only sensors and weapon systems are considered

Figure 26. Regression analysis resulting from effects screening of mean total LCS casualties when considering only sensors and weapon systems for the MIW scenario

#### d. Summary

As the reliance on technology continues to rise, whether that technology is significant or useful will always be in question until it is employed in combat. Such is the case with LCS and its sensors and weapon systems. This section has shown that in each scenario sensors and weapon systems contribute in various levels to the MOEs. In the SUW scenario, while NLOS Pk is significant in the presence of others, none of the sensors or weapons are individually identified as statistically significant, suggesting that

numbers of LCS play a larger role in impacting the MOEs. Hellfire Pk, RAM Pk, SUW MH-60R Pd, and ASW USV Pd are statistically significant in the ASW scenario when using a squadron size of six to ten LCS, and a blue torpedo Pk of 79 percent or more produces higher mean Red casualties in certain situations. The MIW scenario shows that 57mm Pk is statistically significant in predicting mean total LCS casualties, with clearance Pk being significant in the presence of other parameters. While the analysis is unable to provide thresholds for the sensors and weapon systems identified as statistically significant, the results show that certain sensors and weapon systems do contribute to the MOEs.

### **C. FURTHER INSIGHTS**

In addition to addressing the research questions mentioned in Chapter I, further insights have been gained through this research. This section discusses these insights and impacts they may have on an employable LCS squadron.

#### **1. Significance of Submarines in the SUW Scenario**

When conducting the analysis for size and composition of the LCS squadron in the SUW scenario, it was discovered that submarines and not missile boats contributed the most to mean total Blue casualties and mean total LCS casualties. These results suggest that the submarine threat be neutralized first in order to reduce casualties. This introduces a reminder that the operating environment may not be perfectly known, that a threat more lethal than the one LCS is configured for may be present, and further supports the six to ten LCS squadron containing two ASW LCS for the SUW scenario. When conducting a SUW mission, if enemy submarines may be present this analysis shows that transiting at speeds ideal for the search and prosecution of the ASW threat results in lower Blue casualties.

#### **2. Limitations on the ASW Mission**

Previous regression tree analysis of the ASW scenario revealed a disparity suggesting saturation numbers of LCS in some situations and low numbers in others. The regression tree analysis of mean total LCS casualties suggests that ten submarines may be

the most an employed LCS squadron may be able to handle without support. Plotting mean total Blue casualties and mean total LCS casualties versus number of submarines shows that Blue casualties significantly increase in situations where there are more than ten submarines. It also shows a steady, continuous rise in total LCS casualties for the same region. This suggests additional support will be necessary for the LCS squadron in operating environments where there may be more than ten submarines. Figure 27 shows the impact of ten or more submarines on mean total Blue casualties and mean total LCS casualties.

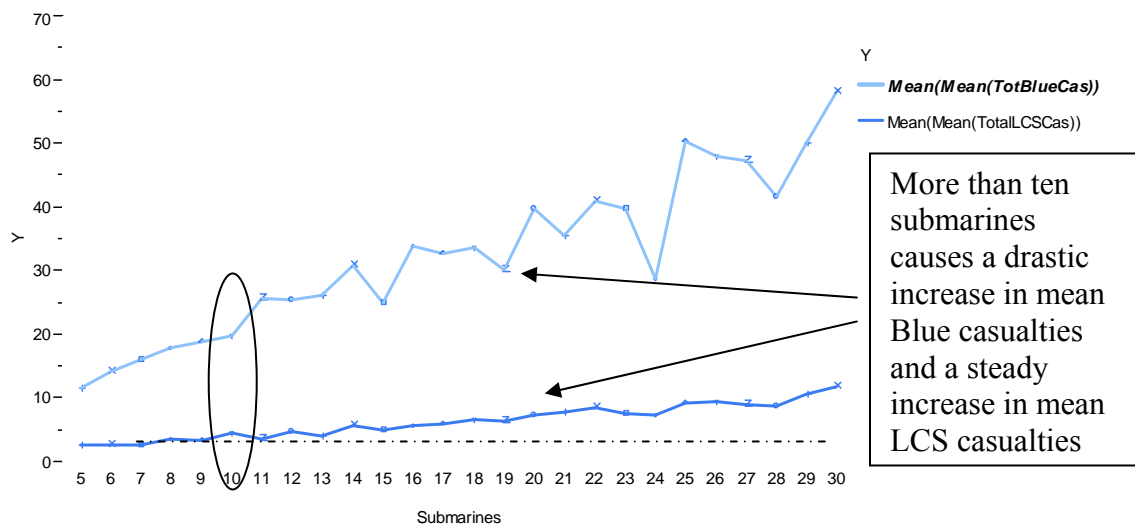


Figure 27. Graph showing the impact of more than ten submarines on mean total Blue casualties and mean total LCS casualties

### 3. Impact of Littoral Combat on the U. S. Navy Mindset

With the advent of missile technology, the engagement of the enemy at sea has been extended. The result of which being the U.S. Navy becoming comfortable with operating in uncontested waters and sending ordnance down range. As such, reports of casualties caused at sea quickly become headlines particularly in the United States, which is casualty adverse. The product of this comfortableness can be detrimental:

The U.S. Navy's bread-and-butter missions for thirty years, these "projection" operations have probably bred complacency about the nature of combat, which is not always so one-sided an affair. (Hughes, 1986)

With mean total Blue casualties ranging from 2.99 to 17.38 and mean total LCS casualties ranging from 0.01 to 6.09, this thesis shows that engagement of the enemy in the littorals produces casualties. Figure 28 shows the distributions of mean total Blue casualties for each warfare area when an employed LCS squadron of six to ten LCS is used. This requires a change of mindset for the U. S. Navy such that casualties due to littoral combat are not only expected but are considered an acceptable cost for the given mission.

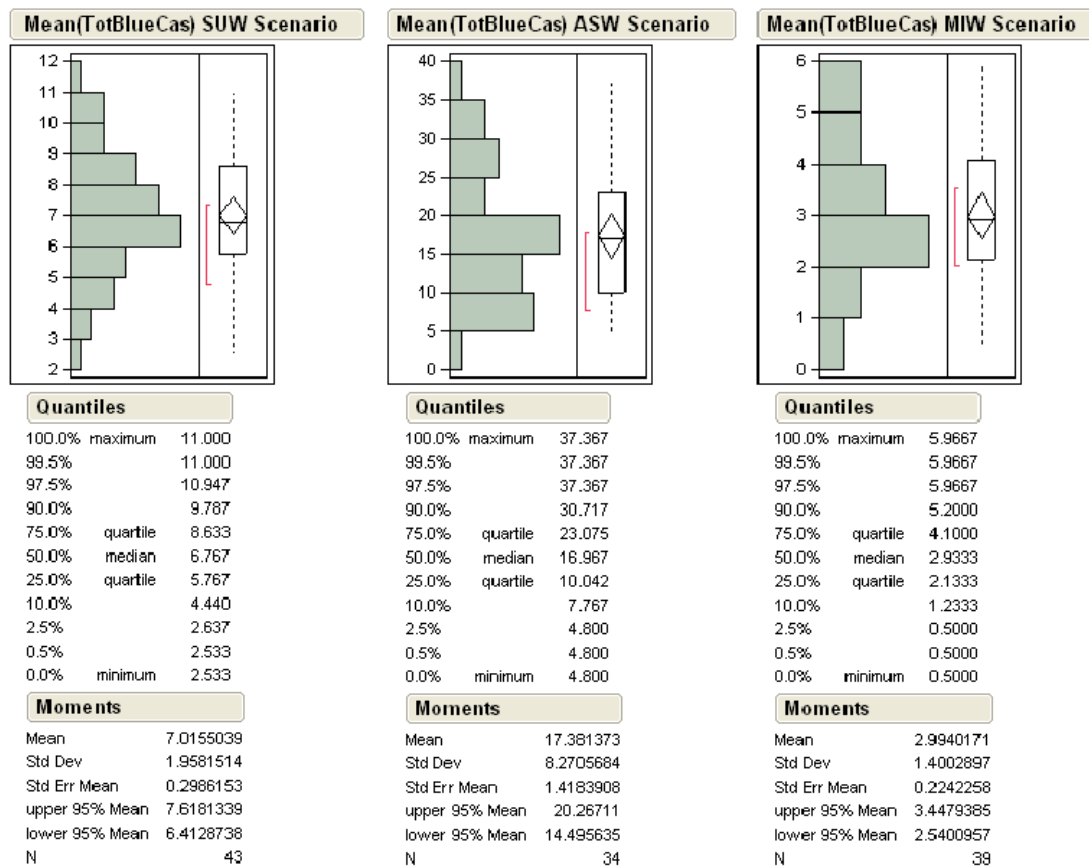


Figure 28. Distribution of mean total Blue casualties for each scenario.

## **V. CONCLUSIONS AND RECOMMENDATIONS**

### **A. RESEARCH SUMMARY**

With every new ship building program comes both questions and assumptions. For LCS, a platform that is designed to face the littoral threat in the post Cold War world, it is no different. This research set out to provide analytic insight into the employment of LCS as a squadron in a stressing operational environment. Through a simulation experiment based on realistic scenarios, this thesis produced detailed analysis regarding the size, composition, and effects of sensors and weapon systems of an employed LCS squadron. The simulation work used for this thesis provides a solid base for future use of agent based models in exploring similar or related topics.

### **B. RESEARCH QUESTIONS**

The goal of this thesis was to address the following questions:

- How many LCS should there be in a squadron?
- What combination of mission packages is needed in the LCS squadron to complete the given focused mission when the possibility of multiple threats exists?
- How effective are sensors and weapon systems with regards to enabling LCS to complete its focused mission?

This section will briefly summarize the answers to these questions.

#### **1. Size of the Employed LCS Squadron**

The resulting data from the simulation experiment are analyzed through multiple regression and regression trees to provide insight into the size of the employed LCS squadron. The analysis shows that a squadron size of six to ten LCS produces lower mean casualties for both the Blue force, and LCS specifically, while producing higher mean Red casualties in each of the warfare areas.

## **2. Composition of the Employed LCS Squadron**

Through the same analytical methods, the composition of the employed LCS squadron was considered. The analysis shows that five SUW LCS and two ASW LCS are recommended for the SUW scenario; five ASW LCS and one SUW LCS are recommended for the ASW scenario; and six MIW LCS and one SUW LCS are recommended for the MIW scenario. It is important to note that the surface threat was varied across the warfare areas. This being the case, the number of SUW LCS should be altered as necessary based on the perceived size of the surface threat. In general, a composition of five LCS configured for the primary threat and two LCS configured for the perceived secondary threat serves as a compositional rule of thumb. While this composition may not be optimal, this thesis shows that it will produce dramatically lower Blue casualties than simply using a squadron of homogeneous composition.

## **3. Effects of Sensors and Weapon Systems**

Different warfare areas rely on technology in different ways. Through multiple regression, regression tree, and effects screening analysis, this thesis shows that sensors and weapon systems play a more significant role in the ASW and MIW scenarios. Since none of the sensors and weapon systems are analytically identified as significant, the war adage that numbers matter is shown to hold true for the SUW scenario. Conversely, several sensors and weapon systems are analytically identified as significant for the ASW and MIW scenarios; specifically Hellfire Pk, RAM Pk, SUW MH-60R Pd, ASW USV Pd, and Blue Torpedo Pk, and 57mm Pk respectively. While unable to provide precise thresholds for most of these systems, this thesis shows that sensors and weapon systems play a significant role in predicting the MOEs.

## **C. FURTHER INSIGHTS**

In addition to addressing the research questions, this thesis produced further insight into the use of an employed LCS squadron. This section briefly summarizes these insights.



### **1. Significance of Submarines in the SUW Scenario**

The use of multiple regression and regression tree analysis shows that the presence of submarines in the SUW scenario is the most significant factor in mean Blue casualties and mean LCS casualties. Since submarines are the secondary threat in the SUW scenario, the employed LCS squadron searched for and engaged the primary threat of missile boats at a high rate of speed. This tactic made use of the RMVs in the ASW mission package infeasible and produced easier targets for the enemy submarines. The results of this thesis shows that the presence of enemy submarines requires the use of ASW tactics (i.e., slower speeds and maximized use of ASW sensors) to produce low mean Blue casualties.

### **2. Limitations on the ASW Mission**

Regression tree analysis of the ASW scenario displays a disparity in the handling of enemy submarines. Suggesting saturation numbers of LCS for low levels of submarines and low numbers of LCS when the threat is large gave rise to the thought that there may be a limit to the number of submarines a squadron of LCS can handle without support. Further analysis shows that in situations where there are ten or more submarines, mean Blue casualties increase drastically and mean LCS casualties steadily rise. The fact that no number or combination of LCS lowered casualties in situations where there are ten or more submarines suggests that additional fleet support should be provided if a LCS squadron is to operate in such an environment.

### **3. Impact of Littoral Combat on the U. S. Navy Mindset**

A significant insight produced by this thesis is that in each scenario the employed LCS squadron suffered casualties. With mean Blue casualties ranging from 2.99 to 17.3 and mean LCS casualties ranging from 0.01 to 6.09 when employing a squadron of six to ten LCS, the Navy should expect casualties when engaging in the littorals. This differs significantly from the detached engagement that the Navy has become accustomed to with the advent of missile technology, and will require a shift in mindset.

#### **4. Simulating Operations**

The benefit of computer simulation is the ability to simulate numerous operations in the littorals without placing a single sailor at risk. This thesis simulated 23,130 littoral combat operations exploring a broad range of values among the variables, which provides insight into a large number of possible outcomes. The analysis of the results provides the lessons learned for these simulated littoral combat operations, which would have been costly in time, money, and blood if conducted in real life. This by no means translates to operational experience, but provides valuable insight for future operations and demonstrates how simulation and data farming techniques can benefit the U.S. Navy.

#### **D. RECOMMENDATIONS**

The results of this thesis support the following recommendations:

- In order to produce low mean Blue casualties and high Red casualties, it is recommended the employed LCS squadron consist of six to ten LCS.
- When deploying an employed LCS squadron for an SUW mission that may contain a submarine threat, it is recommended that a composition of at least five SUW LCS and two ASW LCS be implemented.
- When deploying an employed LCS squadron for an ASW mission that may include a surface threat, it is recommended that a composition of at least five ASW LCS and one SUW LCS be implemented.
- When deploying an employed LCS squadron for an MIW mission that may include a surface threat, it is recommended that a composition of six MIW LCS and at least one SUW LCS be implemented.
- When considering the use of an employed LCS squadron for an ASW mission, it is recommended that additional fleet assets be provided to support the squadron if the expected number of enemy submarines is ten or more.
- In situations where information regarding the disposition of enemy forces is unavailable, it is recommended that the compositional rule of thumb of five LCS configured for the primary threat and two LCS configured for the secondary threat be used.
- Due to the inherent risk of littoral combat, it is recommended that a paradigm shift occur in the U. S. Navy such that both equipment and personnel casualties are expected and accepted.
- When considering the use of an employed LCS squadron for a SUW mission that may contain a submarine threat, it is recommended that the

squadron pursue the SUW threat using tactics that allow for the maximized use of ASW sensors and weapon systems in order to produce lower Blue casualties.

- The use of simulation and data farming helped provide valuable insight in short order for an asset that is not yet deployable. It is recommended that simulation and data farming techniques be used in future U. S. Navy research to guide the development and deployment of new technologies.


## **E. FURTHER RESEARCH**

While working on this thesis, the following items were identified as warranting further research:

- Focused analysis of the sensors and weapon systems under development in order to provide recommended thresholds.
- The possibility of interchanging sensors and weapon systems within the mission packages in order to provide a form of multi-mission capability for LCS.
- Optimization of the mix of sensors and weapon systems in each mission package.
- Possibility of establishing a multi-mission capability for the MH-60R/S to enable asset sharing across a heterogeneous employed LCS squadron.
- Effects of communication or network failure among the unmanned vehicles on Blue force casualties and mission effectiveness.
- Analysis of the impact of a mixed squadron, containing LCS and legacy surface platforms, on Blue force casualties and mission effectiveness.
- Analysis of effects of logistic requirements and alternative modes of support and sustainment for both LCS and its mission packages on Blue force casualties and mission effectiveness.
- Impact of an air threat on the employed LCS squadron.
- Analysis of the impact of a mixed squadron, containing LCS and other non-surface platforms, on Blue force casualties and mission effectiveness.
- Analysis of the effects of maintenance requirements and failure rates of helicopters and unmanned vehicles on Blue force casualties and mission effectiveness.
- Analysis of the impact of using unmanned aerial vehicles in the event of helicopter loss or failure on Blue casualties and mission effectiveness.

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## APPENDIX A. PERSONALITIES AND CAPABILITIES OF AGENTS

**NAVAL  
POSTGRADUATE  
SCHOOL**


### Modeling Summary – Missile Boats

Weapon	Range	Pk	Rounds
C-802	66 nm	.75	4
30 mm	1 nm	.7	3000

**Sensors and Speed:** Basic surface search with a detection range of 20 nm, and classification range of 12 nm. Missile boats transit at a speed of 8 knots, attack at 40 knots, and can travel at 15 knots when injured.

**Personality Summary:** Missile boats commence attack as a group once they detect any blue forces. When attacked by blue, they disperse from the area receiving fire. Their smaller sensor range does not allow them to capitalize on their long range missile capability. Once an enemy is detected they pursue. Number of missile boats is varied through the Nearly Orthogonal Latin Hypercube (NOLH).

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**NAVAL  
POSTGRADUATE  
SCHOOL**

### Modeling Summary – Red Submarines

Weapon	Range	Pk	Rounds
Torpedo	10 nm	.75	18

**Sensors and Speed:** Submarine is assigned a detection range on surface targets of 20 nm but cannot classify until 8 nm. Submarines are assigned an attack speed of 15 knots and a patrol speed of 6 knots. Due to the intended abstractness of this study, no concern was given to the various depth profiles normally associated with ASW problems.

**Personality Summary:** Enemy Submarines lie in waiting for Friendly forces entering the channel. Once an enemy is detected they pursue and use torpedoes. If they are fired upon they commence evasion procedures by taking randomly drawn courses away from blue forces. Number of enemy submarines is varied through the NOLH.

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## Modeling Summary – Merchant Traffic

Sensors and Speed: Merchant traffic is able to detect and classify targets at 20 nm. Due to the importance of timely delivered goods and fuel economy, Merchants always travel at 20 knots. Anchored merchants remain anchored throughout the scenario.

Personality Summary: Merchant traffic is used in the model as a realistic source of surface clutter complicating the operational picture for both red and blue. Neither the friendly forces nor the enemy forces have an interest in investigating, impeding, or attacking merchant traffic. Merchants are able to be attacked and no consideration for their safety is taken into account by either side when engaging the enemy. The number of Merchants will be varied through the NOLH.

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## Modeling Summary – SUW LCS

Weapon	Range	Pk	Rounds
NLOS	22 nm	NOLH	60
Mk 3 57 mm	9 nm	NOLH	500
30 mm	3 nm	NOLH	3000
RAM	10 nm	NOLH	21

Sensors and Speed: For LCS detection and classification are linked because there will be a probability associated with its detection. LCS is assigned a detection range of 50 nm and its Probability of Detection will be varied through the NOLH with a range of .5 – 1.0. LCS has a transit speed of 20 knots, and an attack speed of 40 knots. If injured, LCS will be able to travel at its transit speed.

Personality Summary: The SUW Scenario is designed to model a LCS Squadron transiting a channel to clear it of any surface threats. Upon commencement, SUW LCS are following assigned PIM into the channel with an embarked MH-60R airborne. Upon enemy detection, squadron will detach LCS gaining detection and order pursuit with a kill objective. Once the enemy is neutralized, LCS will return to PIM. Since LCS is a focused mission platform, a SUW LCS will not pursue anything other than a surface threat (i.e. it will not pursue, and cannot detect, a submarine). The number of SUW LCS will be varied through the NOLH.

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## Modeling Summary – SUW MH-60R

Weapon	Range	Pk	Rounds
Hellfire (MH-60R)	5 nm	NOLH	8

**Sensors and Speed:** The MH-60R is assigned a detection range of 75 nm and its probability of detection will be varied through the NOLH with a range of .5 – 1.0. The UAV will have a sensor range of 20 nm and its probability of detection will also be varied through the NOLH with a range of .5 – 1.0. The MH-60R transits at an operational speed of 144 knots, and the UAV will transit at 80 knots.

**Personality Summary:** The assumption is that the LCS will operate with its MH-60R airborne as opposed to the UAV. This being the case, each LCS will have their MH-60R airborne at scenario start. Modeling an initial use of a UAV due to a MH-60R being down because of maintenance is still being considered, but may be left for further research. The MH-60R follows the LCS PIM in station with LCS. Once the MH-60R detects an enemy it will pursue but will maintain a standoff distance of 20 nm until LCS is able to close, due to the short reach of its weaponry. Once LCS has closed the MH-60R, the MH-60R will approach the enemy with the LCS. Since this MH-60R is assigned to an SUW LCS, it will not pursue or attack anything other than a surface threat. Each SUW LCS is assigned 1 SUW MH-60R.

To model the loss of a MH-60R due to combat, the MH-60R is given 100 per cent concealment when it is injured and its sole desire is to find a friendly platform. Once a friendly platform is found, its concealment is returned to 0 per cent and its MH-60R attributes are replaced with those of the UAV. Due to the MH-60R standoff distance this option is not exercised very often.

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## Modeling Summary – ASW LCS

Weapon	Range	Pk	Rounds
Mk 3 57 mm	9 nm	NOLH	500
30 mm	3 nm	NOLH	3000
RAM	10 nm	NOLH	21
.50 Cal MG	1 nm	NOLH	5000

**Sensors and Speeds:** With regards to sensors and speed, the ASW LCS is no different than the SUW LCS.

**Personality Summary:** The ASW LCS is in escort mode for this scenario, thus it is not patrolling a barrier and the SUW LCS is not necessarily following behind the ASW LCS (positions are randomized within the friendly start box at problem start). ASW LCS is assigned the same PIM as SUW LCS. Once an enemy is detected it will pursue. While the ASW LCS has weaponry to engage both surface and subsurface contacts, it will engage enemy submarines with a priority over enemy surface threats. Further, the enemy submarine engagement will be conducted with the MH-60R. Since the ASW LCS does not have a way to deliver an ASW weapon, it is assigned a 10 nm standoff from a detected submarine. Once the subsurface threat is neutralized the ASW LCS will continue on PIM and is available to assist the SUW LCS in a surface engagement.

There is a slight modeling issue regarding the ASW LCS detecting the submarine at 50 nm. This occurs because the submarine is essentially modeled like a surface contact, and the non-ASW assets (SUW LCS and SUW MH-60R/UAV) are simply told not to pursue that specific enemy. While this is a problem, I believe it is resolved through the fact that the ASW LCS cannot engage a submarine due to its lack of organic delivery of an ASW weapon (no SVTT). This being the case, while ASW LCS detects the submarine early the submarine isn't engaged until the MH-60R detects the submarine and pursues. The ASW LCS does act as a torpedo re-loader for the MH-60R which can only carry 3 torpedoes.

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## Modeling Summary – ASW MH-60R

Weapon	Range	Pk	Rounds
Mk 54 Torpedo	8 nm	NOLH	3

**Sensors and Speed:** With regard to speed, the ASW MH-60R is modeled exactly the same as the SUW MH-60R/UAV. For sensors, however, the ASW MH-60R is given a sensor range of 22 nm with a probability of detection that will be varied through the NOLH with a range of .5 – 1.0. This is to model the A/N-AQS-22 system that the MH-60R will be using to find the submarine. The A/N-AQS-22 is a system that is designed to be operated by a MH-60R in a hover, but I am not capable of modeling that in MANA. This may be one of the modeling issues I concede to the ASW field.

**Personality Summary:** The ASW MH-60R acts just like the SUW MH-60R/UAV (see above). Once an enemy is detected the ASW MH-60R will pursue and engage. Since the ASW MH-60R only has 3 torpedoes, once its primary ammunition is expended it transits to a reloading waypoint. Once the ASW MH-60R reaches the waypoint it is given 3 more torpedoes and is able to re-engage the enemy. A reloading waypoint is used to simulate the ASW MH-60R returning to its respective ASW LCS for an ammunition reload. Once the subsurface enemy is neutralized, the ASW MH-60R will continue to transit PIM and may assist in a surface engagement.

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## Modeling Summary – ASW USV

Sensor	Range	Pd
UTAS	5 nm	NOLH
UDS	5 nm	NOLH

**Sensors and Speed:** For sensors an Unmanned Surface Vehicle is assigned per sensor, and is given a range of 5 nm with a probability of detection that will be varied through the NOLH with a range of .5 – 1.0. A speed of advance of 12 knots is given to the USVs as they operate much like the ASW MH-60R (dipping sonar) but with a lower maximum speed in between dips.

**Personality Summary:** The ASW USVs transit at a speed of 12 knots while looking for enemy submarines. Once a submarine is detected the ASW USV will close to help localize the enemy, and pass the information to the ASW LCS for prosecution.

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## Modeling Summary – ASW RMV

Sensor	Range	Pd
RTA (MFTA)	5 nm	NOLH
RTAS	5 nm	NOLH

Sensors and Speed: For sensors an Remotely Manned Vehicle is assigned per sensor, and is given a range of 5 nm with a probability of detection that will be varied through the NOLH with a range of .5 – 1.0. A speed of advance of 12 knots is given to the RMVs as they operate much like the ASW MH-60R (dipping sonar) but with a lower maximum speed in between dips.

Personality Summary: The ASW RMVs transit at a speed of 12 knots while looking for enemy submarines. Once a submarine is detected the ASW RMV will close to help localize the enemy, and pass the information to the ASW LCS for prosecution.

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## Modeling Summary – MIW LCS

Weapon	Range	Pk	Rounds
Mk 3 57 mm	9 nm	NOLH	500
30 mm	3 nm	NOLH	3000
RAM	10 nm	NOLH	21
.50 Cal MG	1 nm	NOLH	5000

Sensors and Speeds: With regards to sensors and speed, the MIW LCS is no different than the SUW LCS.

Personality Summary: The MIW LCS and its off board vehicles are transiting the littoral area to clear it of mines, and, as such, all off board vehicles are deployed at problem start. SUW LCS are transiting the channel with the MIW LCS to protect them in the event of a missile boat attack. While the MIW LCS has weaponry to engage both surface and subsurface contacts, it will engage mines with a priority over enemy surface threats. Further, the mine engagement will be conducted with the MH-60S. Once the subsurface threat is neutralized the MIW LCS will continue transiting the channel and is available to assist the SUW LCS in the event of a surface engagement.

There is a slight modeling issue regarding the MIW LCS detecting the mines at 50 nm. This occurs because the mine is essentially modeled like a surface contact, and the non-MIW assets (SUW LCS and SUW MH-60R/UAV) are simply told not to pursue that specific enemy. While this is a problem, I believe it is resolved through the fact that the MIW LCS cannot engage a mine. This being the case, while MIW LCS detects the mine early the mine cannot be cleared until the MH-60S detects the mine and pursues. The MIW LCS does act as a re-loader for the MH-60S.

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## Modeling Summary – MIW MH-60S

Weapon	Range	Pk	Rounds
Clearance	8 nm	NOLH	3

**Sensors and Speed:** For sensors the ASW MH-60R is given a sensor range of 5 nm with a probability of detection that will be varied through the NOLH with a range of .5 – 1.0. The sensor is abstractly modeling the detection capabilities of the MIW MH-60S, and not a specific system. The MIW MH-60S needs to refuel every 3 hrs.

**Personality Summary:** Once a mine is detected by or is passed to the MIW MH-60S, it will pursue and engage. The MIW MH-60S is the only clearance platform available to LCS in this scenario. It has the use of a generic weapon to neutralize mines, and is required to transit to a waypoint to simulate reloading. The characteristics of the MH-60S clearance weapon is to abstractly simulate the different systems that may be used to neutralize/clear mines.

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## Modeling Summary – MIW USV

Sensor	Range	Pd
Mk104	5 nm	NOLH

**Sensors and Speed:** For sensors an Unmanned Surface Vehicle is given a range of 5 nm with a probability of detection that will be varied through the NOLH with a range of .5 – 1.0. A speed of 25 knots is given to the USVs.

**Personality Summary:** The MIW USVs transit at a speed of 25 knots while looking for mines, but will stay within 15 nm of MIW LCS. Once a mine is detected the MIW USV will close to help localize the enemy, and pass the information to the MIW LCS for prosecution.

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## Modeling Summary – MIW RMV

Sensor	Range	Pd
AN/AQS-20A	5 nm	NOLH

Sensors and Speed: For sensors an Remotely Manned Vehicle is given a range of 5 nm with a probability of detection that will be varied through the NOLH with a range of .5 – 1.0. The RMV can operate at speeds ranging from 8 – 15 kts depending on the towing length of the sensor. A speed of 12 knots is given to the RMVs as an average speed.

Personality Summary: The MIW RMVs transit at a speed of 12 knots while looking for mines. Once a mine is detected the MIW RMV will close to help localize the enemy, and pass the information to the MIW LCS for prosecution.

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## APPENDIX B. EXPERIMENTAL DESIGNS

This appendix illustrates the Nearly Orthogonal Latin Hypercubes (NOLH) used to conduct the simulation experiment, and their associated correlation matrices. Since no changes were made to the preliminary designs prior to running the full experiment, only the full designs are shown. Due to the size of the full designs, only the first 50 rows are provided. Correlation values larger than 0.03 are highlighted in yellow for easy identification.

### A. EXPLORATORY DESIGN

low level	1	5	0	0	0
high level	30	50	1	1	1
decimals	0	0	3	3	3
factor name	LCS	Swarm	Pd	Pc	Pi
	22	7	0.359	0.328	0.125
	29	37	0.109	0.422	0.344
	27	21	0.953	0.219	0.297
	20	45	0.719	0.453	0.063
	28	26	0.188	0.016	0.094
	16	46	0.234	0.484	0.156
	23	13	0.531	0.031	0.25
	25	39	0.922	0.313	0.375
	21	6	0.016	0.813	0.406
	29	36	0.484	0.766	0
	16	6	0.969	0.531	0.203
	30	28	0.688	0.922	0.172
	17	15	0.328	0.641	0.391
	24	30	0.422	0.891	0.266
	18	20	0.781	0.953	0.438
	20	31	0.547	0.719	0.141
	26	25	0.391	0.125	0.672
	17	44	0.266	0.344	0.578
	22	23	0.563	0.297	0.781
	19	38	0.859	0.063	0.547
	25	14	0.406	0.094	0.984
	24	42	0	0.156	0.516
	30	23	0.797	0.25	0.969
	18	50	0.828	0.375	0.688
	19	16	0.094	0.594	0.813
	23	33	0.156	1	0.766
	25	9	0.75	0.797	0.531
	27	43	0.625	0.828	0.922
	28	18	0.125	0.609	0.641
	21	47	0.344	0.734	0.891
	20	11	0.703	0.563	0.953
	26	35	0.938	0.859	0.719
	16	28	0.5	0.5	0.5
	9	48	0.641	0.672	0.875
	2	18	0.891	0.578	0.656
	4	34	0.047	0.781	0.703
	11	10	0.281	0.547	0.938
	3	29	0.813	0.984	0.906
	15	9	0.766	0.516	0.844
	8	42	0.469	0.969	0.75
	6	16	0.078	0.688	0.625
	10	49	0.984	0.188	0.594
	2	19	0.516	0.234	1
	15	49	0.031	0.469	0.797
	1	27	0.313	0.078	0.828
	14	40	0.672	0.359	0.609
	7	25	0.578	0.109	0.734
	13	35	0.219	0.047	0.563
	11	24	0.453	0.281	0.859
	5	30	0.609	0.875	0.328
	14	11	0.734	0.656	0.422
	9	32	0.438	0.703	0.219
	12	17	0.141	0.938	0.453
	6	41	0.594	0.906	0.016
	7	13	1	0.844	0.484
	1	32	0.203	0.75	0.031
	13	5	0.172	0.625	0.313
	12	39	0.906	0.406	0.188
	8	22	0.844	0	0.234
	6	46	0.25	0.203	0.469
	4	12	0.375	0.172	0.078
	3	37	0.875	0.391	0.359
	10	8	0.656	0.266	0.109
	11	44	0.297	0.438	0.047
	5	20	0.063	0.141	0.281

Correlation Matrix

	LCS	Swarm	Pd	Pc	Pi
LCS	1				
Swarm	-0.00791	1			
Pd	0.002397	0.006462	1		
Pc	-0.00298	0.003743	-4.4E-08	1	
Pi	-0.01044	0.003707	-4.4E-08	-4.4E-08	1

## B. SUW FULL DESIGN

elements[]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
low level	1	0	5	1	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
high level	30	5	50	5	5	1	1	1	1	1	1	1	1	1	1	1
decimals	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3
factor name	SUW LCS	ASW LCS	Red MB	Red Sub	Merchants	57 mm Pk	.50 Cal Pk	Ram Pk	LCS Pd	SUW H Pd	Hellfire Pk	NLOS Pk	30 mm Pk	ASW H Pd	Torp Pk	ASW O Pd
1	13	4	32	3	3	0.949	1	0.938	0.594	0.533	0.619	0.693	0.531	0.592	0.67	0.697
2	4	2	43	5	4	0.766	0.986	0.922	0.771	0.805	0.813	0.871	1	0.943	0.756	0.512
3	6	3	10	3	5	0.906	0.971	0.945	0.822	0.682	0.602	0.623	0.564	0.572	0.969	0.916
4	13	1	23	4	4	0.873	0.939	0.975	0.576	0.773	0.969	0.891	0.982	0.977	0.822	0.791
5	12	3	33	3	5	0.896	0.877	0.844	0.533	0.908	0.543	0.527	0.66	0.539	0.752	0.58
6	14	2	48	2	4	0.953	0.867	0.977	0.861	0.729	0.92	0.881	0.92	0.854	0.957	0.713
7	2	3	25	1	3	0.76	0.883	0.793	0.836	0.793	0.502	0.635	0.654	0.66	0.572	0.955
8	12	0	22	3	5	0.871	0.85	0.84	0.742	0.535	0.732	0.766	0.904	0.826	0.713	0.953
9	3	3	47	4	2	0.893	0.869	0.99	0.588	0.691	0.973	0.615	0.729	0.715	0.592	0.828
10	15	0	44	4	0	0.805	0.783	0.775	0.979	0.875	0.701	0.842	0.879	0.975	0.566	0.779
11	5	5	27	5	2	0.752	0.988	0.799	0.951	0.643	0.822	0.605	0.605	0.701	0.824	0.551
12	3	1	8	4	2	0.834	0.885	0.811	0.746	0.994	0.719	0.746	0.99	0.818	0.859	0.717
13	9	5	33	1	2	0.898	0.822	0.832	0.686	0.969	0.883	0.604	0.521	0.736	0.906	0.834
14	2	1	37	2	1	0.9	0.994	0.756	0.857	0.59	0.676	0.889	0.836	0.83	0.801	0.934
15	9	3	7	3	1	0.764	0.881	0.781	0.869	0.986	0.783	0.633	0.523	0.574	0.555	0.652
16	12	1	17	1	2	0.861	0.969	0.928	0.553	0.752	0.506	0.764	0.887	0.789	0.588	0.684
17	9	3	41	4	4	0.686	0.82	0.83	0.578	0.684	0.754	0.826	0.561	0.664	0.666	0.668
18	15	1	41	3	3	0.641	0.926	0.838	0.887	0.893	0.953	0.621	0.805	0.814	0.738	0.586
19	7	4	26	3	4	0.52	0.936	0.895	0.838	0.615	0.621	0.861	0.578	0.549	0.846	0.764
20	7	1	17	4	4	0.635	0.889	0.959	0.732	0.717	0.902	0.51	0.928	0.904	0.887	0.924
21	11	3	40	2	4	0.535	0.992	0.982	0.688	0.871	0.514	0.898	0.555	0.584	0.963	0.648
22	15	2	32	2	5	0.568	0.934	0.912	0.883	0.559	0.871	0.521	0.975	0.992	0.742	0.637
23	12	4	27	3	3	0.742	0.891	0.863	0.844	0.869	0.609	0.947	0.586	0.678	0.648	0.992
24	7	2	20	2	4	0.537	0.908	0.828	0.738	0.693	0.742	0.752	0.867	0.871	0.627	0.84
25	8	3	41	5	1	0.693	0.768	0.998	0.535	0.744	0.811	0.916	0.646	0.527	0.705	0.883
26	15	1	46	3	2	0.521	0.842	0.943	0.879	0.951	0.607	0.627	0.742	0.98	0.65	0.756
27	4	4	27	4	2	0.721	0.803	0.904	0.859	0.621	0.836	0.775	0.645	0.729	0.777	0.711
28	7	0	17	4	2	0.684	0.848	0.771	0.736	0.902	0.762	0.711	0.783	0.902	0.99	0.621
29	8	4	45	2	1	0.703	0.918	0.887	0.744	0.988	0.875	0.887	0.615	0.689	0.924	0.902
30	6	1	29	1	1	0.58	0.875	0.787	0.949	0.604	0.578	0.715	0.898	0.869	0.82	0.693
31	15	4	13	3	2	0.559	0.836	0.955	0.855	0.832	0.844	0.797	0.705	0.529	0.561	0.592
32	4	2	16	2	1	0.699	0.77	0.967	0.605	0.736	0.711	0.57	0.818	0.949	0.609	0.533
33	14	3	43	3	3	1	0.551	0.854	0.666	0.699	0.57	0.514	0.791	0.713	0.57	0.59
34	11	2	39	4	4	0.986	0.734	0.789	0.953	0.791	0.807	0.982	0.582	0.875	0.689	0.613
35	8	4	20	3	4	0.971	0.594	0.785	0.789	0.658	0.605	0.588	0.908	0.545	0.775	0.922
36	6	1	26	4	4	0.939	0.627	0.984	0.715	0.799	0.926	0.975	0.607	0.795	0.771	0.873
37	10	3	29	2	5	0.877	0.604	0.916	0.709	0.865	0.523	0.654	0.973	0.727	0.734	0.529
38	12	2	36	2	4	0.867	0.547	0.791	0.787	0.588	0.984	0.924	0.617	0.922	0.781	0.574
39	10	3	23	2	4	0.883	0.74	0.846	0.877	0.77	0.564	0.656	0.896	0.662	0.596	0.93
40	14	2	19	3	4	0.85	0.629	0.857	0.734	0.652	0.677	0.932	0.748	0.867	0.557	0.982
41	6	4	49	4	2	0.869	0.807	0.855	0.582	0.6	0.85	0.676	0.813	0.676	0.553	0.818
42	7	1	44	4	2	0.783	0.895	0.809	0.988	0.855	0.748	0.822	0.611	0.844	0.584	0.855
43	5	5	15	4	2	0.988	0.748	0.973	0.955	0.641	0.828	0.594	0.848	0.709	0.9	0.656
44	1	1	13	4	2	0.885	0.666	0.813	0.629	0.961	0.709	0.988	0.762	0.988	0.896	0.768
45	7	4	34	1	1	0.822	0.602	0.754	0.598	0.977	0.854	0.523	0.916	0.518	0.857	0.734
46	5	1	43	2	1	0.994	0.6	0.951	0.9	0.564	0.535	0.836	0.625	0.74	0.949	0.805
47	5	3	11	2	2	0.881	0.736	0.795	0.93	0.92	0.73	0.563	0.873	0.734	0.523	0.604
48	11	1	15	2	2	0.969	0.639	0.773	0.604	0.619	0.631	0.941	0.76	0.816	0.521	0.549
49	3	4	34	4	5	0.68	0.686	0.762	0.504	0.689	0.537	0.936	0.859	0.553	0.633	0.539
50	8	0	49	3	5	0.574	0.641	0.961	0.801	0.826	1	0.643	0.672	0.746	0.504	0.523

	SUW LCS	ASW LCS	Red MB	Red Sub	Merchants	57 mm Pk	.50 Cal Pk	Ram Pk	LCS Pd	SUW H Pd	Hellfire Pk	NLOS Pk	30 mm Pk	ASW H Pd	Torp Pk	ASW O Pd
SUW LCS	1															
ASW LCS	-0.013456	1														
Red MB	0.000576	0.00561	1													
Red Sub	-0.005267	-0.021084	0.022342	1												
Merchants	0.012379	0.000429	-0.007894	-0.016869	1											
57 mm Pk	-0.001289	0.016836	0.002811	0.021747	0.001769	1										
.50 Cal Pk	-0.000456	-0.001144	-0.002239	0.00671	0.020929	-2.88E-09	1									
Ram Pk	0.002217	-0.002252	-0.000585	0.032938	0.019231	-2.88E-09	-2.88E-09	1								
LCS Pd	0.00119	-0.00395	-0.003184	-0.028436	0.000536	-0.002098	0.0012476	0.000493	1							
SUW H Pd	0.000507	-0.004093	-0.000319	-0.00741	0.055852	-0.000697	-0.0006873	5.74E-06	-0.003554	1						
Hellfire Pk	0.003604	-0.006398	0.000914	0.017922	-0.014816	0.000413	5.558E-06	-0.002123	0.001026	-0.00135638	1					
NLOS Pk	0.002456	0.02302	0.002261	0.04909	-0.013941	-0.00061	0.000852	-0.000868	0.001876	8.1736E-05	0.00032	1				
30 mm Pk	-0.00546	-0.017891	0.001133	0.010557	0.027077	-0.001945	-0.0013873	0.000737	-6.62E-05	-0.00197711	-0.000416	-0.002106	1			
ASW H Pd	-0.00953	0.005487	-0.001944	0.001551	-0.010187	0.000623	0.0008137	0.001034	0.001039	-0.00101145	0.000895	5.69E-05	0.000669	1		
Torp Pk	0.004909	-0.007238	0.000914	0.012589	0.021787	0.000981	-4.152E-05	0.001067	-9.3E-05	-0.00140365	0.001877	2.17E-05	-0.00103	-0.001199	1	
ASW O Pd	-0.00532	0.002895	0.000951	-0.004503	0.012028	-0.000501	0.0021512	-0.000777	0.000511	-0.00281137	-0.000577	-3.21E-05	0.002938	-0.0018446	0.001099	1

## C. ASW FULL DESIGN

Elements[]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Low Level	0	1	0	5	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
High Level	7	30	20	30	5	1	1	1	1	1	1	1	1	1	1	1	1
Decimals	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3
Factor	SUW LCS	ASW LCS	Red MB	Red Sub	Merchants	57mm Pk	.50 Cal Pk	RAM Pk	LCS Pd	SUW H Pd	Hellfire Pk	NLOS Pk	30 mm Pk	ASW H Pd	Torp Pk	USV Pd	RMV Pd
1	3	27	12	20	3	0.949	1	0.938	0.594	0.533	0.619	0.693	0.531	0.592	0.67	0.697	0.723
2	1	13	17	29	4	0.766	0.986	0.922	0.771	0.805	0.813	0.871	1	0.943	0.756	0.512	0.531
3	1	18	2	19	5	0.906	0.971	0.945	0.822	0.682	0.602	0.623	0.564	0.572	0.969	0.916	0.783
4	3	6	8	21	4	0.873	0.939	0.975	0.576	0.773	0.969	0.891	0.982	0.977	0.822	0.791	0.895
5	3	17	12	15	5	0.896	0.877	0.844	0.533	0.908	0.543	0.527	0.66	0.539	0.752	0.58	0.574
6	3	12	19	9	4	0.953	0.867	0.977	0.861	0.729	0.92	0.881	0.92	0.854	0.957	0.713	0.691
7	0	19	9	8	3	0.76	0.883	0.793	0.836	0.793	0.502	0.635	0.654	0.66	0.572	0.955	0.957
8	3	2	7	15	5	0.871	0.85	0.84	0.742	0.535	0.732	0.766	0.904	0.826	0.713	0.953	0.865
9	1	16	19	21	2	0.893	0.869	0.99	0.588	0.691	0.973	0.615	0.729	0.715	0.592	0.828	0.703
10	3	3	17	23	0	0.805	0.783	0.775	0.979	0.875	0.701	0.842	0.879	0.975	0.566	0.779	0.721
11	1	28	10	29	2	0.752	0.988	0.799	0.951	0.643	0.822	0.605	0.605	0.701	0.824	0.551	0.885
12	0	5	1	23	2	0.834	0.885	0.811	0.746	0.994	0.719	0.746	0.99	0.818	0.859	0.717	0.799
13	2	29	13	7	2	0.898	0.822	0.832	0.686	0.969	0.883	0.604	0.521	0.736	0.906	0.834	0.629
14	0	9	14	8	1	0.9	0.994	0.756	0.857	0.59	0.676	0.889	0.836	0.83	0.801	0.934	0.711
15	2	19	1	17	1	0.764	0.881	0.781	0.869	0.986	0.783	0.633	0.523	0.574	0.555	0.652	0.92
16	3	9	5	7	2	0.861	0.969	0.928	0.553	0.752	0.506	0.764	0.887	0.789	0.588	0.684	0.854
17	2	16	16	25	4	0.686	0.82	0.83	0.578	0.684	0.754	0.826	0.561	0.664	0.666	0.668	0.914
18	3	9	16	20	3	0.641	0.926	0.838	0.887	0.893	0.953	0.621	0.805	0.814	0.738	0.586	0.943
19	1	24	9	18	4	0.52	0.936	0.895	0.838	0.615	0.621	0.861	0.578	0.549	0.846	0.764	0.693
20	1	7	6	22	4	0.635	0.889	0.959	0.732	0.717	0.902	0.51	0.928	0.904	0.887	0.924	0.643
21	2	16	16	10	4	0.535	0.992	0.982	0.688	0.871	0.514	0.898	0.555	0.584	0.963	0.648	0.959
22	3	11	12	10	5	0.568	0.934	0.912	0.883	0.559	0.871	0.521	0.975	0.992	0.742	0.637	0.709
23	3	24	10	17	3	0.742	0.891	0.863	0.844	0.869	0.609	0.947	0.586	0.678	0.648	0.992	0.551
24	2	12	7	12	4	0.537	0.908	0.828	0.738	0.693	0.742	0.752	0.867	0.871	0.627	0.84	0.5
25	2	16	16	27	1	0.693	0.768	0.998	0.535	0.744	0.811	0.916	0.646	0.527	0.705	0.883	0.883
26	3	8	18	18	2	0.521	0.842	0.943	0.879	0.951	0.607	0.627	0.742	0.98	0.65	0.756	0.758
27	1	24	10	25	2	0.721	0.803	0.904	0.859	0.621	0.836	0.775	0.645	0.729	0.777	0.711	0.564
28	1	4	5	24	2	0.684	0.848	0.771	0.736	0.902	0.762	0.711	0.783	0.902	0.99	0.621	0.652
29	2	25	18	10	1	0.703	0.918	0.887	0.744	0.988	0.875	0.887	0.615	0.689	0.924	0.902	0.768
30	1	8	11	7	1	0.58	0.875	0.787	0.949	0.604	0.578	0.715	0.898	0.869	0.82	0.693	0.945
31	3	27	4	17	2	0.559	0.836	0.955	0.855	0.832	0.844	0.797	0.705	0.529	0.561	0.592	0.576
32	1	15	5	11	1	0.699	0.77	0.967	0.605	0.736	0.711	0.57	0.818	0.949	0.609	0.533	0.713
33	3	20	17	18	3	1	0.551	0.854	0.666	0.699	0.57	0.514	0.791	0.713	0.57	0.59	0.594
34	2	14	15	22	4	0.986	0.734	0.789	0.953	0.791	0.807	0.982	0.582	0.875	0.689	0.613	0.527
35	2	25	7	20	4	0.971	0.594	0.785	0.789	0.658	0.605	0.588	0.908	0.545	0.775	0.922	0.996
36	1	8	9	22	4	0.939	0.627	0.984	0.715	0.799	0.926	0.975	0.607	0.795	0.771	0.873	0.994
37	2	19	11	9	5	0.877	0.604	0.916	0.709	0.865	0.523	0.654	0.973	0.727	0.734	0.529	0.598
38	3	10	14	11	4	0.867	0.547	0.791	0.787	0.588	0.984	0.924	0.617	0.922	0.781	0.574	0.621
39	2	17	8	13	4	0.883	0.74	0.846	0.877	0.77	0.564	0.656	0.896	0.662	0.596	0.93	0.842
40	3	10	6	17	4	0.85	0.629	0.857	0.734	0.652	0.877	0.932	0.748	0.867	0.557	0.982	0.891
41	1	24	20	21	2	0.869	0.607	0.855	0.582	0.6	0.85	0.676	0.813	0.676	0.553	0.818	0.682
42	2	6	17	26	2	0.783	0.695	0.809	0.988	0.855	0.748	0.822	0.611	0.844	0.584	0.855	0.52
43	1	30	4	27	2	0.988	0.748	0.973	0.955	0.641	0.828	0.594	0.848	0.709	0.9	0.656	0.867
44	0	5	4	24	2	0.885	0.666	0.813	0.629	0.961	0.709	0.988	0.762	0.988	0.896	0.768	0.846
45	2	26	13	5	1	0.822	0.602	0.754	0.598	0.977	0.854	0.523	0.916	0.518	0.857	0.734	0.502
46	1	7	17	8	1	0.994	0.6	0.951	0.9	0.564	0.535	0.836	0.625	0.74	0.949	0.805	0.676
47	1	20	3	10	2	0.881	0.736	0.795	0.93	0.92	0.73	0.563	0.873	0.734	0.523	0.604	0.967
48	3	5	4	10	2	0.969	0.639	0.773	0.604	0.619	0.631	0.941	0.76	0.816	0.521	0.549	0.811
49	0	23	13	23	5	0.68	0.686	0.762	0.504	0.689	0.537	0.936	0.859	0.553	0.633	0.539	0.939
50	2	3	20	19	5	0.574	0.641	0.961	0.801	0.826	1	0.643	0.672	0.746	0.504	0.523	0.908

	SUW LCS	ASW LCS	Red MB	Red Sub	Merchants	57mm Pk	.50 Cal Pk	RAM Pk	LCS Pd	SUW H Pd	Hellfire Pk	NLOS Pk	30 mm Pk	ASW H Pd	Torp Pk	USV Pd	RMV Pd
SUW LCS	1																
ASW LCS	0.019014	1															
Red MB	-0.004872	0.007462	1														
Red Sub	0.013336	0.005079	-0.003963	1													
Merchants	-0.018113	-0.014435	-0.009802	0.007575	1												
57mm Pk	0.002133	-0.002358	-0.007655	0.002374	0.0017693	1											
.50 Cal Pk	0.012576	0.001941	-0.00189	-0.002196	0.0209287	-2.88E-09	1										
RAM Pk	0.009661	0.000235	0.004172	-0.001091	0.0192308	-2.88E-09	-2.88E-09	1									
LCS Pd	0.006761	0.00534	-0.005281	-0.004278	0.0005361	-0.002098	0.001248	0.000493	1								
SUW H Pd	-0.006882	0.002111	-0.001058	-0.004695	0.0558517	-0.000697	-0.000687	5.74E-06	-0.003554	1							
Hellfire Pk	-0.005965	-0.000219	-0.000231	-0.000129	-0.014816	0.000413	5.56E-06	-0.002123	0.001026	-0.001356	1						
NLOS Pk	0.007092	-0.004688	-4.69E-06	0.000983	-0.013941	-0.00061	0.000852	-0.000868	0.001876	8.174E-05	0.00032	1					
30 mm Pk	-0.008099	0.000176	-0.000116	-0.000667	0.0270769	-0.001945	-0.001387	0.000737	-6.62E-05	-0.001977	-0.000416	-0.002106	1				
ASW H Pd	-0.00601	-0.000627	-0.003932	0.004122	-0.010187	0.000623	0.000814	0.001034	0.001039	-0.001011	0.000895	5.69E-05	0.000669	1			
Torp Pk	0.004778	0.003157	0.001312	-0.001227	0.0217866	0.000981	-4.15E-05	0.001067	-9.3E-05	-0.001404	0.001877	2.17E-05	-0.00103	-0.001199	1		
USV Pd	-0.004643	0.001728	0.001649	-0.001908	0.0120282	-0.000501	0.002151	-0.000777	0.000511	-0.002811	-0.000577	-3.21E-05	0.002938	-0.0018446	0.001099	1	
RMV Pd	-0.024431	0.001083	0.002841	-0.005901	0.0028238	-0.000579	-0.00107	0.000865	0.002415	0.0021769	0.001414	-0.00017	0.00024	-0.0017013	0.000219	0.00217	1

## D. MIW FULL DESIGN

Elements[]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Low Level	1	0	0	20	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
High Level	30	7	15	200	5	1	1	1	1	1	1	1	1	1	1	1	1
Decimals	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3
Factor	MIW LCS	SUW LCS	Red MB	Mines	Merchants	LCS Pd	MIW H Pd	SUW H Pd	NLOS Pk	57mm Pk	30mm Pk	RAM Pk	.50 Cal Pk	Clearance Pk	Hellfire Pk	MIW USV Pd	MIW RMV Pd
1	13	6	9	130	3	0.949	1	0.938	0.594	0.533	0.619	0.693	0.531	0.592	0.67	0.697	0.723
2	4	3	13	192	4	0.766	0.986	0.922	0.771	0.805	0.813	0.871	1	0.943	0.756	0.512	0.531
3	6	4	2	121	5	0.906	0.971	0.945	0.822	0.682	0.602	0.623	0.564	0.572	0.969	0.916	0.783
4	13	1	6	134	4	0.873	0.939	0.975	0.576	0.773	0.969	0.891	0.982	0.977	0.822	0.791	0.895
5	12	4	9	93	5	0.896	0.877	0.844	0.533	0.908	0.543	0.527	0.66	0.539	0.752	0.58	0.574
6	14	3	14	49	4	0.953	0.867	0.977	0.861	0.729	0.92	0.881	0.92	0.854	0.957	0.713	0.691
7	2	4	7	41	3	0.76	0.883	0.793	0.836	0.793	0.502	0.635	0.654	0.66	0.572	0.955	0.957
8	12	0	6	92	5	0.871	0.85	0.84	0.742	0.535	0.732	0.766	0.904	0.826	0.713	0.953	0.865
9	3	4	14	133	2	0.893	0.869	0.99	0.588	0.691	0.973	0.615	0.729	0.715	0.592	0.828	0.703
10	15	1	13	149	0	0.805	0.783	0.775	0.979	0.875	0.701	0.842	0.879	0.975	0.566	0.779	0.721
11	5	7	7	193	2	0.752	0.988	0.799	0.951	0.643	0.822	0.605	0.605	0.701	0.824	0.551	0.885
12	3	1	1	151	2	0.834	0.885	0.811	0.746	0.994	0.719	0.746	0.99	0.818	0.859	0.717	0.799
13	9	7	9	33	2	0.898	0.822	0.832	0.686	0.969	0.883	0.604	0.521	0.736	0.906	0.834	0.629
14	2	2	11	45	1	0.9	0.994	0.756	0.857	0.59	0.676	0.889	0.836	0.83	0.801	0.934	0.711
15	9	4	1	107	1	0.764	0.881	0.781	0.869	0.986	0.783	0.633	0.523	0.574	0.555	0.652	0.92
16	12	2	4	33	2	0.861	0.969	0.928	0.553	0.752	0.506	0.764	0.887	0.789	0.588	0.684	0.854
17	9	4	12	161	4	0.686	0.82	0.83	0.578	0.684	0.754	0.826	0.561	0.664	0.666	0.668	0.914
18	15	2	12	130	3	0.641	0.926	0.838	0.887	0.893	0.953	0.621	0.805	0.814	0.738	0.586	0.943
19	7	6	7	111	4	0.52	0.936	0.895	0.838	0.615	0.621	0.861	0.578	0.549	0.846	0.764	0.963
20	7	1	4	140	4	0.635	0.889	0.959	0.732	0.717	0.902	0.51	0.928	0.904	0.887	0.924	0.643
21	11	4	12	57	4	0.535	0.992	0.982	0.688	0.871	0.514	0.998	0.555	0.584	0.963	0.648	0.959
22	15	2	9	56	5	0.568	0.934	0.912	0.883	0.559	0.871	0.521	0.975	0.992	0.742	0.637	0.709
23	12	5	7	105	3	0.742	0.891	0.863	0.844	0.869	0.609	0.947	0.586	0.678	0.648	0.992	0.551
24	7	3	5	70	4	0.537	0.908	0.828	0.738	0.693	0.742	0.752	0.867	0.871	0.627	0.84	0.5
25	8	4	12	182	1	0.693	0.768	0.998	0.535	0.744	0.811	0.916	0.646	0.527	0.705	0.883	0.883
26	15	2	14	116	2	0.521	0.842	0.943	0.879	0.951	0.607	0.627	0.742	0.98	0.65	0.756	0.758
27	4	6	7	166	2	0.721	0.803	0.904	0.859	0.621	0.836	0.775	0.645	0.729	0.777	0.711	0.564
28	7	1	4	154	2	0.684	0.848	0.771	0.736	0.902	0.762	0.711	0.783	0.902	0.99	0.621	0.652
29	8	6	13	57	1	0.703	0.918	0.887	0.744	0.988	0.875	0.887	0.615	0.689	0.924	0.902	0.768
30	6	2	8	37	1	0.58	0.875	0.787	0.949	0.604	0.578	0.715	0.898	0.869	0.82	0.693	0.945
31	15	6	3	106	2	0.559	0.836	0.955	0.855	0.832	0.844	0.797	0.705	0.529	0.561	0.592	0.576
32	4	3	4	66	1	0.699	0.77	0.967	0.605	0.736	0.711	0.57	0.818	0.949	0.609	0.533	0.713
33	14	5	13	116	3	0.551	0.854	0.666	0.669	0.689	0.57	0.514	0.791	0.713	0.57	0.59	0.594
34	11	3	11	143	4	0.986	0.734	0.789	0.953	0.791	0.807	0.882	0.582	0.875	0.689	0.613	0.527
35	8	6	5	129	4	0.971	0.594	0.785	0.789	0.658	0.605	0.588	0.908	0.545	0.775	0.922	0.596
36	6	2	7	145	4	0.939	0.627	0.984	0.715	0.799	0.926	0.975	0.607	0.795	0.771	0.873	0.994
37	10	4	8	50	5	0.877	0.604	0.916	0.709	0.865	0.523	0.654	0.973	0.727	0.734	0.529	0.598
38	12	2	10	65	4	0.867	0.547	0.791	0.787	0.588	0.984	0.924	0.617	0.922	0.781	0.574	0.621
39	10	4	6	79	4	0.883	0.74	0.846	0.877	0.77	0.564	0.656	0.896	0.662	0.596	0.93	0.842
40	14	2	5	103	4	0.85	0.629	0.857	0.734	0.652	0.877	0.932	0.748	0.867	0.557	0.982	0.891
41	6	5	15	135	2	0.869	0.607	0.855	0.582	0.6	0.85	0.676	0.813	0.676	0.553	0.818	0.682
42	7	1	13	173	2	0.783	0.695	0.809	0.988	0.855	0.748	0.822	0.611	0.844	0.584	0.855	0.52
43	5	7	3	177	2	0.988	0.748	0.973	0.955	0.641	0.828	0.594	0.848	0.709	0.9	0.656	0.867
44	1	1	3	160	2	0.885	0.666	0.813	0.629	0.961	0.709	0.988	0.762	0.988	0.896	0.768	0.846
45	7	6	10	23	1	0.822	0.602	0.754	0.598	0.977	0.854	0.523	0.916	0.518	0.857	0.734	0.502
46	5	2	13	44	1	0.994	0.6	0.951	0.9	0.564	0.535	0.836	0.625	0.74	0.949	0.805	0.676
47	5	4	2	59	2	0.881	0.736	0.795	0.93	0.92	0.73	0.563	0.873	0.734	0.523	0.604	0.967
48	11	1	3	53	2	0.969	0.639	0.773	0.604	0.619	0.631	0.941	0.76	0.816	0.521	0.549	0.811
49	3	5	10	153	5	0.68	0.686	0.762	0.504	0.689	0.537	0.936	0.859	0.553	0.633	0.539	0.939
50	8	0	15	122	5	0.574	0.641	0.961	0.801	0.826	1	0.643	0.672	0.746	0.504	0.523	0.908

	MIW LCS	SUW LCS	Red MB	Mines	Merchants	LCS Pd	MIW H Pd	SUW H Pd	NLOS Pk	57mm Pk	30mm Pk	RAM Pk	.50 Cal Pk	Clearance Pk	Hellfire Pk	MIW USV Pd	MIW RMV Pd
MIW LCS	1																
SUW LCS	-0.009548	1															
Red MB	-0.0092	0.013054	1														
Mines	0.001471	-0.017017	0.001986	1													
Merchants	0.012379	-0.008449	-0.0052	0.007248	1												
LCS Pd	-0.001289	-0.017743	-0.005651	0.000194	0.001769	1											
MIW H Pd	-0.000456	0.016523	-0.006656	-0.000604	0.020929	-2.88E-09	1										
SUW H Pd	0.002217	0.007658	-0.001522	-0.000351	0.019231	-2.88E-09	-2.88E-09	1									
NLOS Pk	0.000119	0.008488	-0.005867	0.001453	0.000536	-0.002098	0.001248	0.000493	1								
57mm Pk	0.000507	-0.010682	0.004147	3.6E-05	0.055852	-0.000697	-0.000687	5.743E-06	-0.003554	1							
30mm Pk	0.003604	0.002544	-0.007679	-0.002384	-0.014816	0.000413	5.56E-06	-0.0021232	0.001026	-0.001356	1						
RAM Pk	0.002456	0.007216	0.001233	0.00014	-0.013941	-0.00061	0.000852	-0.0008678	0.001876	8.17E-05	0.00032	1					
.50 Cal Pk	-0.00546	-0.000299	0.003291	-0.001784	0.027077	-0.001945	-0.001387	0.0007366	-6.62E-05	-0.001977	-0.000416	-0.002106	1				
Clearance Pk	-0.00953	0.008943	0.001245	0.002015	-0.010187	0.000623	0.000814	0.0010342	0.001039	-0.001011	0.000895	5.69E-05	0.000669	1			
Hellfire Pk	0.004909	0.034771	-0.003316	4.22E-05	0.021787	0.000981	-4.15E-05	0.0010674	-9.3E-05	-0.001404	0.001877	2.17E-05	-0.00103	-0.001199022	1		
MIW USV Pd	-0.00532	0.000571	0.002182	-0.001384	0.012028	-0.000501	0.002151	-0.000777	0.000511	-0.002811	-0.000577	-3.21E-05	0.002938	-0.00184459	0.0010995	1	
MIW RMV Pd	-0.002367	-0.001376	0.001898	-0.000943	0.002824	-0.000579	-0.00107	0.0008646	0.002415	0.002177	0.001414	-0.00017	0.00024	-0.001701316	0.0002191	0.002170427	1



## APPENDIX C. RUBY CODE FOR RUNNING EXPERIMENT

Three different programs were written in order to run the simulation experiment. The first program used the input data from the Nearly Orthogonal Latin Hypercube (NOLH) to make 257 patches for the base warfare scenario. The second program applied these patches to the base warfare scenario creating 257 XML files for the simulation to run. The third program was used to run the simulation experiment, and label the output files appropriately

### A. CODE CREATING PATCHES

The code displayed was used for the SUW scenario. Due to the differences between the three scenarios, each scenario needed its own patch creating program.

**mana\_help\_SUW.rb**

```
def makePatch(str)
  result=[]
  elements=[]
  counter = 0
  fh=File.open("SUWInput.csv")
  while line=fh.gets
    counter= counter + 1
    elements=line.strip.split(",")
    orig=File.open(str)
    result=orig.readlines
    result[5]=result[5].sub("2", elements[0].to_s)
    result[9]=result[9].sub("7000", (elements[11].to_f * 10000).to_i.to_s)
    result[13]=result[13].sub("7000", (elements[5].to_f * 10000).to_i.to_s)
    result[17]=result[17].sub("7000", (elements[12].to_f * 10000).to_i.to_s)
    result[21]=result[21].sub("7000", (elements[7].to_f * 10000).to_i.to_s)
    result[25]=result[25].sub("7000", (elements[8].to_f * 10000).to_i.to_s)
    result[29]=result[29].sub("7000", (elements[11].to_f * 10000).to_i.to_s)
    result[33]=result[33].sub("7000", (elements[5].to_f * 10000).to_i.to_s)
    result[37]=result[37].sub("7000", (elements[12].to_f * 10000).to_i.to_s)
    result[41]=result[41].sub("7000", (elements[7].to_f * 10000).to_i.to_s)
    result[45]=result[45].sub("7000", (elements[8].to_f * 10000).to_i.to_s)
    result[49]=result[49].sub("7000", (elements[5].to_f * 10000).to_i.to_s)
    result[53]=result[53].sub("7000", (elements[12].to_f * 10000).to_i.to_s)
    result[57]=result[57].sub("7000", (elements[7].to_f * 10000).to_i.to_s)
    result[61]=result[61].sub("7000", (elements[8].to_f * 10000).to_i.to_s)
    result[65]=result[65].sub("45", elements[2].to_s)
    result[69]=result[69].sub("2", elements[0].to_s)
    result[73]=result[73].sub("7000", (elements[10].to_f * 10000).to_i.to_s)
    result[77]=result[77].sub("6000", (elements[9].to_f * 10000).to_i.to_s)
    result[81]=result[81].sub("7000", (elements[10].to_f * 10000).to_i.to_s)
    result[85]=result[85].sub("6000", (elements[9].to_f * 10000).to_i.to_s)
```

```

result[89]=result[89].sub("6000", (elements[9].to_f * 10000).to_i.to_s)
result[118]=result[118].sub("6000", (elements[9].to_f * 10000).to_i.to_s)
result[125]=result[125].sub("4", elements[4].to_s)
result[129]=result[129].sub("4", elements[4].to_s)
result[133]=result[133].sub("4", elements[4].to_s)
result[137]=result[137].sub("4", elements[3].to_s)
result[141]=result[141].sub("2", elements[1].to_s)
result[145]=result[145].sub("7000", (elements[5].to_f * 10000).to_i.to_s)
result[149]=result[149].sub("7000", (elements[6].to_f * 10000).to_i.to_s)
result[153]=result[153].sub("7000", (elements[7].to_f * 10000).to_i.to_s)
result[157]=result[157].sub("7000", (elements[8].to_f * 10000).to_i.to_s)
result[161]=result[161].sub("7000", (elements[5].to_f * 10000).to_i.to_s)
result[165]=result[165].sub("7000", (elements[6].to_f * 10000).to_i.to_s)
result[169]=result[169].sub("7000", (elements[7].to_f * 10000).to_i.to_s)
result[173]=result[173].sub("7000", (elements[8].to_f * 10000).to_i.to_s)
result[177]=result[177].sub("7000", (elements[5].to_f * 10000).to_i.to_s)
result[181]=result[181].sub("7000", (elements[6].to_f * 10000).to_i.to_s)
result[185]=result[185].sub("7000", (elements[7].to_f * 10000).to_i.to_s)
result[189]=result[189].sub("7000", (elements[8].to_f * 10000).to_i.to_s)
result[193]=result[193].sub("2", elements[1].to_s)
result[197]=result[197].sub("7000", (elements[14].to_f * 10000).to_i.to_s)
result[201]=result[201].sub("6000", (elements[13].to_f * 10000).to_i.to_s)
result[205]=result[205].sub("7000", (elements[14].to_f * 10000).to_i.to_s)
result[209]=result[209].sub("6000", (elements[13].to_f * 10000).to_i.to_s)
result[213]=result[213].sub("6000", (elements[13].to_f * 10000).to_i.to_s)
result[217]=result[217].sub("6000", (elements[13].to_f * 10000).to_i.to_s)
result[221]=result[221].sub("7000", (elements[14].to_f * 10000).to_i.to_s)
result[225]=result[225].sub("6000", (elements[13].to_f * 10000).to_i.to_s)
result[229]=result[229].sub("7000", (elements[14].to_f * 10000).to_i.to_s)
result[233]=result[233].sub("6000", (elements[13].to_f * 10000).to_i.to_s)
result[237]=result[237].sub("7000", (elements[14].to_f * 10000).to_i.to_s)
result[241]=result[241].sub("6000", (elements[13].to_f * 10000).to_i.to_s)
result[245]=result[245].sub("2", (elements[1].to_f * 2).to_i.to_s)
result[249]=result[249].sub("6000", (elements[15].to_f * 10000).to_i.to_s)
result[257]=result[257].sub("6000", (elements[15].to_f * 10000).to_i.to_s)
result[265]=result[265].sub("6000", (elements[15].to_f * 10000).to_i.to_s)
newName= "design" + counter.to_s + ".patch"
hope=File.new(newName, File::CREAT|File::TRUNC|File::RDWR, 0644)
for i in 0...270
  hope.write(result[i])
end
end
end
makePatch(ARGV[0])

```

## B. CODE CONVERTING PATCHES TO XMLS

This program converts the patches into the XMLs that will run the simulation. Since each scenario had to patch a different base file, this code was altered to reflect the scenario being worked on. The code below was used for the MIW scenario:

### **patch\_toxml.rb**

```
suffix = ".patch"
if ARGV.length > 0
  prefix = ARGV.shift
  suffix = ARGV.shift if ARGV.length > 0
  Dir["*" + suffix].each do |fname|
    if fname =~ /^#{prefix}/
      bn = File.basename(fname, ".patch")
      cmdLine = "patch " + "BaseMIW.xml " + fname + " -o " + bn + ".xml"
      puts `#{cmdLine}`
    end
  end
else
  puts "You must supply the prefix to be stripped as a command line argument."
end
```

## C. CODE TO RUN XMLS

This program runs the 257 different XML files through MANA using the command line, and labels the output CSV file with the design number. This code was altered depending on whether preliminary runs or full runs were desired.

### **runxml.rb**

```
suffix=".xml"
if ARGV.length > 0
  prefix = ARGV.shift
  suffix = ARGV.shift if ARGV.length > 0
  Dir["*" + suffix].each do |fname|
    if fname =~ /^#{prefix}/
      bn = File.basename(fname, ".xml")
      cmdLine = "MANAC -f" + fname + " -m" + bn + ".csv" + " -n30"
      puts `#{cmdLine}`
    end
  end
end
```

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## APPENDIX D. RUBY CODE FOR DATA PROCESSING

Ruby programs were written in order to make the output files easy to manipulate for analysis. The first program added the design number to the output file, while the second gleaned the necessary information and created one large output file for each scenario.

### A. CODE TO ADD DESIGN

Since every run was replicated 30 times in each scenario, the same Ruby program was able to be used to add the design number to the output file.

#### **addDesign.rb**

```
suffix=".csv"
if ARGV.length > 0
  prefix = ARGV.shift
  suffix = ARGV.shift if ARGV.length > 0
  Dir["*" + suffix].each do |fname|
    if fname =~ /#{prefix}/
      number = fname.chomp.sub(/#{prefix}/, "").sub(/_.*\./,
        ".").sub(/#{suffix}/, "")
      results=[]
      orig=File.open(fname)
      results=orig.readlines
      bn=File.basename(fname, ".csv")
      newName=bn + "clean" + suffix
      hope=File.new(newName, File::CREAT|File::TRUNC|File::RDWR, 0644)
      results[5].insert(0, "Design,")
      for i in 6...40
        results[i].insert(0, number + ",")
      end
      for i in 0...40
        hope.write(results[i])
      end
    end
  end
end
end
```

## B. CODE TO GLEAN AND COMBINE DATA

The 257 output files needed to be combined into a single output file per scenario. This program was used to achieve that end, as well as to glean the necessary information from each individual output file. Since each scenario had different names for the agents, each scenario had its own version of this program. This program was used for the SUW scenario.

### **cleanSteps.rb**

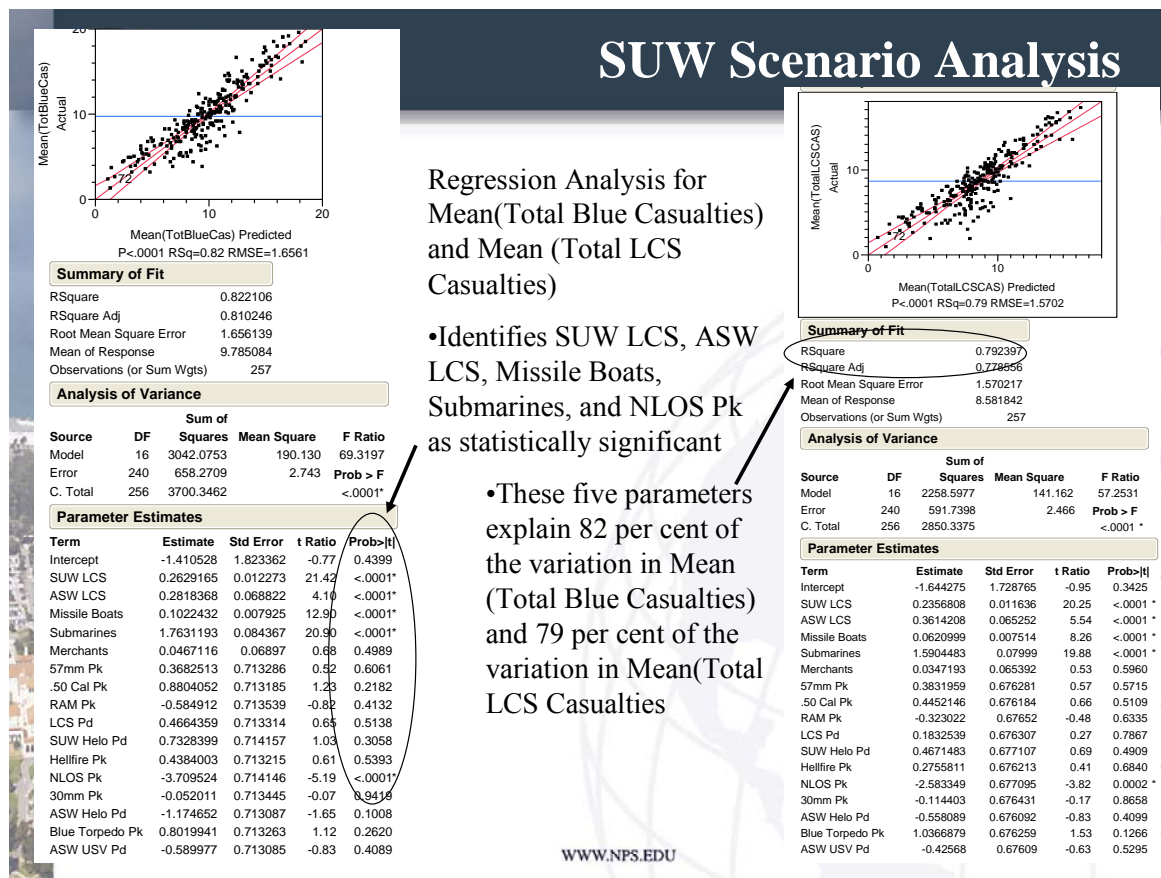
```
def cleanData(str)
  results=[]
  header=["Design, Run, Seed, TotBlueCas, TotRedCas, BlueReachGoal,
    RedReachGoal, Steps, SUWLCSCas, MBCas, SUWHeloCas, OutboundCas,
    InboundCas, AnchoredCas, RedSubCas, ASWLCSCas, ASWHeloCas,
    ASWUSVCas, SUWLCSInj, MBInj, SUWHeloInj, OutboundInj, InboundInj,
    AnchoredInj, RedSubInj, ASWLCSInj, ASWHeloInj, ASWUSVInj\n"]
  newName="SUW30RunResults.csv"
  hope=File.new(newName, File::CREAT|File::TRUNC|File::RDWR, 0644)
  hope.write(header)
  suffix = ".csv"
  if ARGV.length > 0
    prefix = ARGV.shift
    suffix = ARGV.shift if ARGV.length > 0
    Dir["*" + suffix].each do |fname|
      if fname =~ /#{prefix}/
        orig=File.open(fname)
        results=orig.readlines
        for i in 6...36
          hope.write(results[i])
        end
      end
    end
  end
  puts "Data is cleaned. Good luck with the analysis."
end

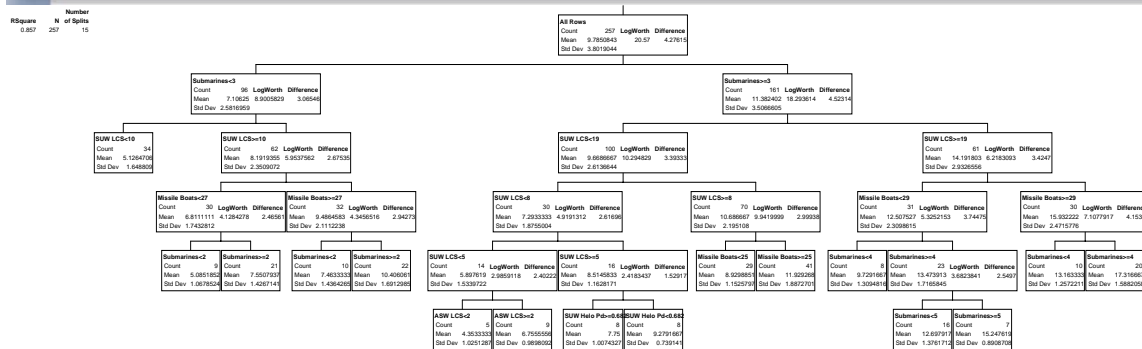
puts "Cleaning Data...please wait."
test = ARGV[0]
cleanData(test)
```

## APPENDIX E. GRAPHS, CHARTS, AND TREES

This appendix provides the graphs, charts, and trees associated with analysis provided in Chapter IV.

### A. SUW SCENARIO

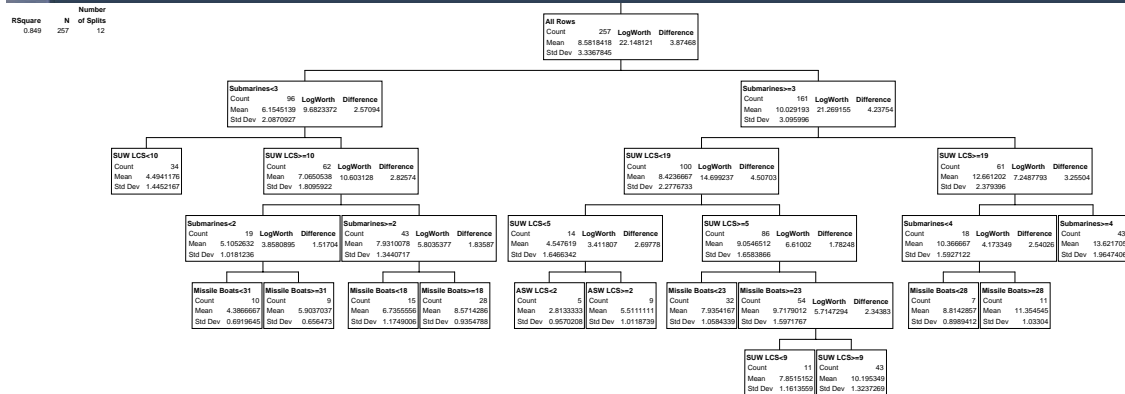




## Regression tree for Mean(Total Blue Casualties)

- Submarines play a significant role
- Suggested maximum of SUW LCS is 10 when there are less than 3 submarines
- If greater than 3 submarines and less than 5 SUW LCS then approximately 2 ASW LCS are necessary to reduce casualties
  - 4 SUW LCS + 2 ASW LCS
- Recommend setting 6 LCS as lower bound and 10 LCS as upper bound





## Regression tree for Mean(Total LCS Casualties)

- Supports squadron size of 6 – 10 LCS
  - Upper bound of 10 LCS due to SUW LCS split if less than 3 submarines
  - 4 SUW LCS + 2 ASW LCS recommended if greater than 3 submarines

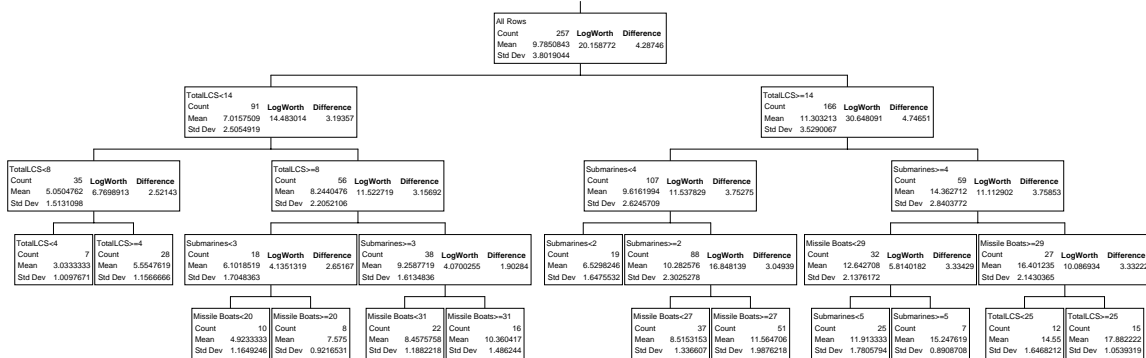
30

WWW.NPS.EDU



RSquare  
0.849

Number  
N of Splits  
257 12



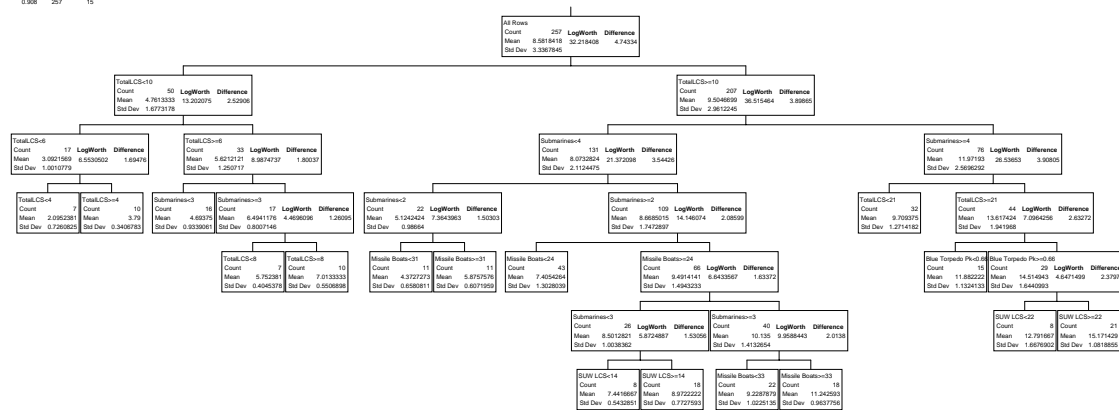
## Regression tree for Mean(Total Blue Casualties) with Total LCS

- First split supports upper bound of 10 for LCS squadron
- Split under less than 14 Total LCS supports 6 – 10 range for LCS squadron
  - When less than 8 total LCS, there is potential for low mean casualties
  - When greater than 8 total LCS, there is potential for lower mean casualties than if there were less than 8 total LCS

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# SUW Scenario Analysis

RSquare	N	Number of Splits
0.908	257	15



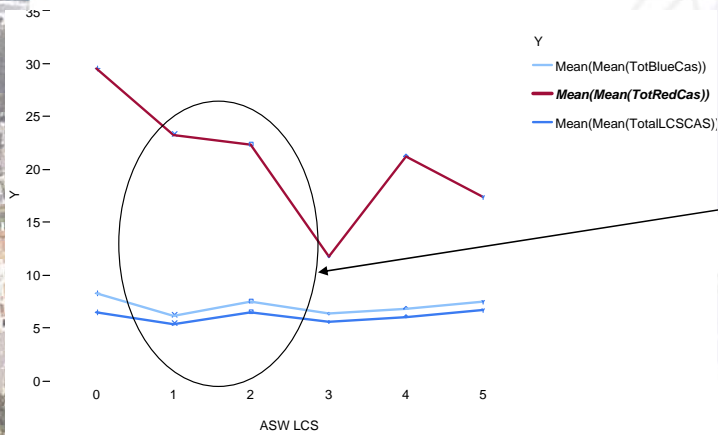
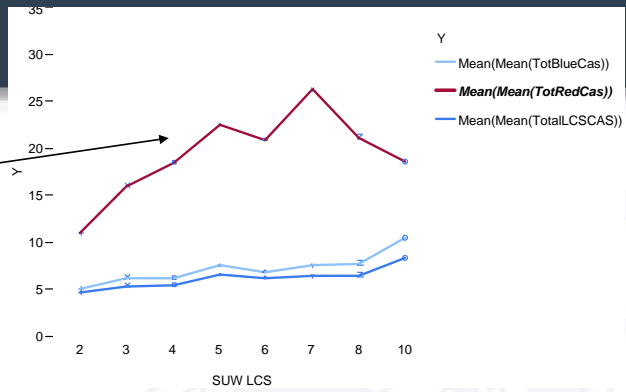
### Regression tree for Mean(Total LCS Casualties) with Total LCS

- Initial split supports upper bound of 10 for LCS squadron
- Split under less than 10 Total LCS supports 6 – 10 range for LCS squadron

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5 or more SUW LCS produces  
high enemy casualties with minimal  
increases  
In mean casualties



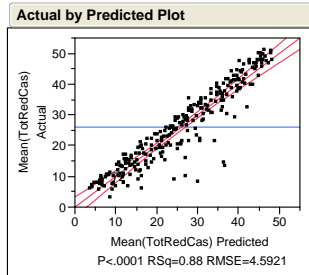
1 to 2 ASW LCS decrease  
mean casualties while producing  
high enemy casualties

# SUW Scenario Analysis

## Regression analysis of Mean(Total Red Casualties)

- Identifies SUW LCS, Missile Boats and Submarines as statistically significant

These parameters explain 88 per cent of the variation in mean(total red casualties)



**Summary of Fit**

RSquare	0.883291
RSquare Adj	0.87551
Root Mean Square Error	4.592101
Mean of Response	25.97224
Observations (or Sum Wgts)	257

**Analysis of Variance**

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	16	38303.052	2393.94	113.5247
Error	240	5060.975	21.09	Prob > F
C. Total	256	43364.026		<.0001*

**Parameter Estimates**

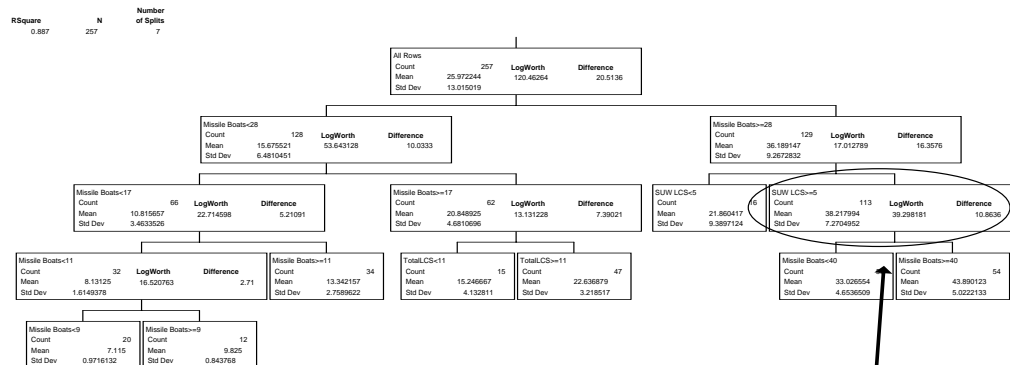
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-5.792525	5.055775	-1.15	0.2531
SUW LCS	0.3750139	0.03403	11.02	<.0001*
ASW LCS	-0.069168	0.190829	-0.36	0.7173
Missile Boats	0.9000335	0.021974	40.96	<.0001*
Submarines	-0.796196	0.23393	-3.40	0.0008*
Merchants	0.0655455	0.191239	0.34	0.7321
57mm Pk	-0.265871	1.977783	-0.13	0.8932
.50 Cal Pk	0.1244315	1.977501	0.06	0.9499
RAM Pk	-0.16522	1.978483	-0.08	0.9335
LCS Pd	2.6179374	1.977859	1.32	0.1869
SUW Helo Pd	2.8205804	1.980198	1.42	0.1556
Hellfire Pk	0.1107346	1.977586	0.06	0.9554
NLOS Pk	0.6462713	1.980166	0.33	0.7444
30mm Pk	-1.145601	1.978223	-0.58	0.5631
ASW Helo Pd	-1.884775	1.977231	-0.95	0.3414
Blue Torpedo Pk	3.5827487	1.977718	1.81	0.0713
ASW USV Pd	-1.637953	1.977225	-0.83	0.4083

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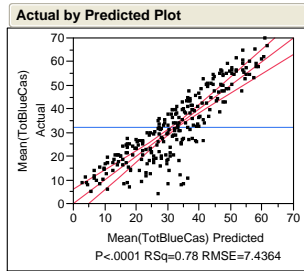
# SUW Scenario Analysis



Regression tree for Mean(Total Red Casualties)

- In this case high means are good
- Split support the 6 – 10 range for LCS squadron, and suggests at least 5 SUW LCS in the squadron

## B. ASW SCENARIO



**Summary of Fit**

RSquare	0.779098
RSquare Adj	0.763385
Root Mean Square Error	7.436363
Mean of Response	32.28288
Observations (or Sum Wgts)	257

**Analysis of Variance**

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	46613.371	2741.96	49.5839
Error	239	13216.580	55.30	
C. Total	256	59829.951		Prob > F <.0001*

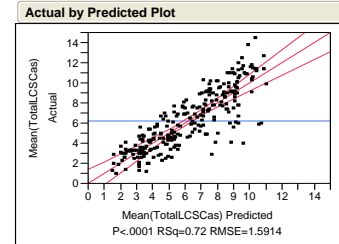
**Parameter Estimates**

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-12.39747	8.546467	-1.45	0.1482
SUW LCS	-0.012952	0.224487	-0.06	0.9540
ASW LCS	0.9289995	0.055104	16.86	<.0001*
Missile Boats	0.1603528	0.079816	2.01	0.0457*
Submarines	1.5045575	0.06387	23.56	<.0001*
Merchants	-0.07163	0.309691	-0.23	0.8173
57mm Pk	-1.581282	3.201851	-0.49	0.6219
.50 Cal Pk	-1.835145	3.202291	-0.57	0.5671
RAM Pk	-0.680444	3.202599	-0.21	0.8319
LCS Pd	-0.025925	3.20236	-0.01	0.9935
SUW Helo Pd	-0.496341	3.20707	-0.15	0.8771
Hellfire Pk	-0.155968	3.201929	-0.05	0.9612
NLOS Pk	0.5007613	3.202355	0.16	0.8759
30mm Pk	2.4038233	3.203252	0.75	0.4537
ASW Helo Pd	-0.009224	3.201797	-0.00	0.9977
Blue Torpedo Pk	-0.445869	3.202855	-0.14	0.8894
USV Pd	2.1240302	3.201832	0.66	0.5077
RMV Pd	3.6230887	3.201973	1.13	0.2590

- Regression analysis of Mean(Total Blue Casualties)
  - Identifies ASW LCS, Missile Boats, and Submarines as statistically significant
  - These parameters explain 78 per cent of the variance in mean(total Blue Casualties)

- Regression analysis of Mean(Total LCS Casualties)
  - Identifies Missile Boats, Submarines, LCS Pd, SUW LCS, and ASW LCS as statistically significant
  - These parameters explain 72 per cent of the variance in mean(total LCS casualties)

## ASW Scenario Analysis



**Summary of Fit**

RSquare	0.720773
RSquare Adj	0.700912
Root Mean Square Error	1.591372
Mean of Response	6.231388
Observations (or Sum Wgts)	257

**Analysis of Variance**

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	1562.3658	91.9039	36.2903
Error	239	605.2588	2.5325	
C. Total	256	2167.6246		Prob > F <.0001*

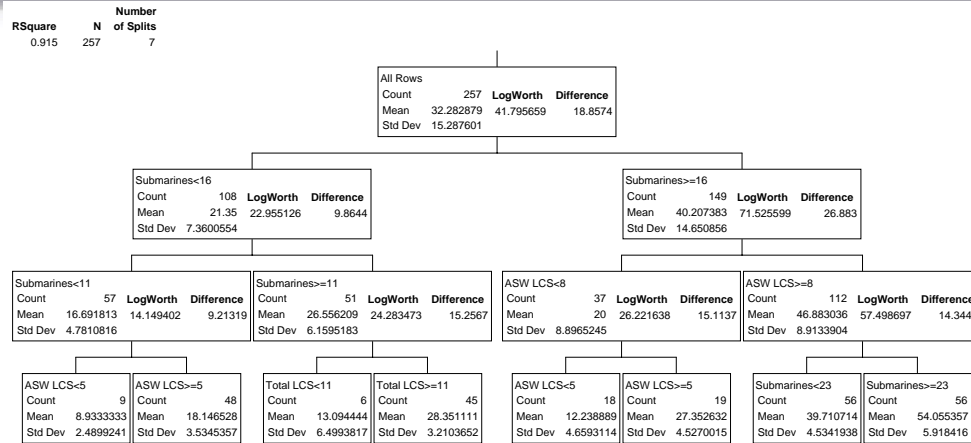
**Parameter Estimates**

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-1.472689	1.828932	-0.81	0.4215
Missile Boats	0.0492174	0.017081	2.88	0.0043 *
Submarines	0.3288678	0.013668	24.06	<.0001 *
Merchants	-0.021775	0.066273	-0.33	0.7428
57mm Pk	-0.469199	0.685192	-0.68	0.4942
.50 Cal Pk	-0.24503	0.685286	-0.35	0.7210
RAM Pk	0.3956914	0.685352	0.58	0.5642
LCS Pd	1.6686916	0.685301	2.43	0.0156 *
SUW Helo Pd	-0.759964	0.686309	-1.11	0.2693
Hellfire Pk	0.6354867	0.685209	0.93	0.3546
NLOS Pk	-0.931967	0.6853	-1.36	0.1751
30mm Pk	0.8137339	0.685492	1.19	0.2364
ASW Helo Pd	0.5358093	0.68518	0.78	0.4350
Blue Torpedo Pk	-0.046055	0.685407	-0.07	0.9465
USV Pd	-0.623956	0.685188	-0.91	0.3634
RMV Pd	0.7068329	0.685218	1.03	0.3033
SUW LCS	0.1790624	0.04804	3.73	0.0002 *
ASW LCS	-0.024317	0.011792	-2.06	0.0403 *

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# ASW Scenario Analysis



- Mean(Total Blue Casualties) with Total LCS
  - Significant factor is number of submarines
  - Splits for both less than and greater than 16 submarines support a squadron size of 6 – 10 LCS
  - Suggests that 5 ASW LCS are necessary

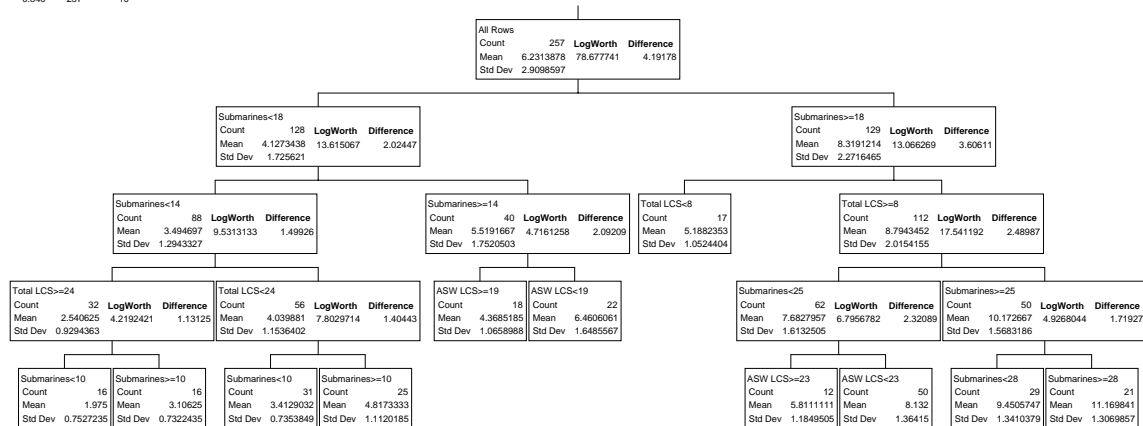




# ASW Scenario Analysis

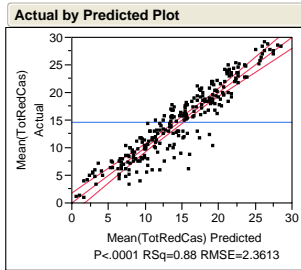
RSquare  
0.840

Number  
N of Splits  
257  
10



- Mean(Total LCS Casualties) with Total LCS
  - Significant factor is number of submarines
  - Suggests that at certain levels either a saturation is needed (i.e. 24 LCS for less than 14 submarines) or the threat is too large for LCS to handle (i.e. less than 8 LCS for more than 18 submarines)
    - Splits on the left hand side suggest that 10 submarines may be the threshold for LCS

# ASW Scenario Analysis



**Summary of Fit**

RSquare 0.877865

RSquare Adj 0.869178

Root Mean Square Error 2.361317

Mean of Response 14.55681

Observations (or Sum Wgts) 257

**Analysis of Variance**

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	9578.439	563.438	101.0502
Error	239	1332.621	5.576	Prob > F
C. Total	256	10911.059		<.0001*

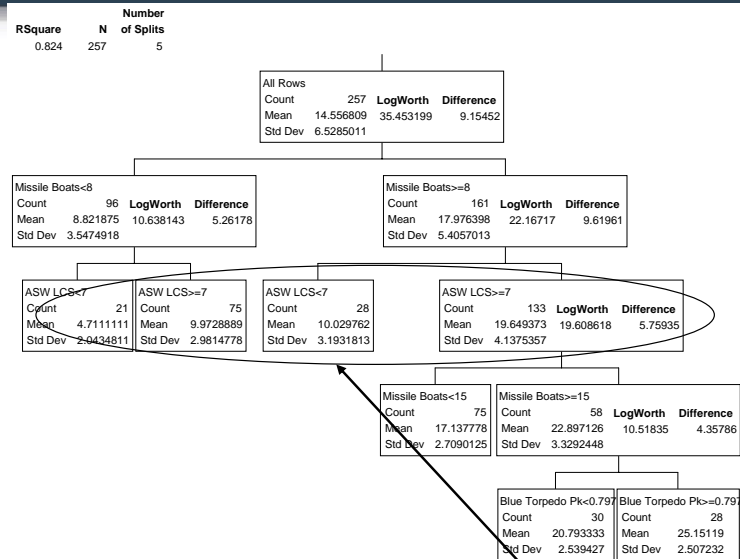
**Parameter Estimates**

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-9.090568	2.713816	-3.35	0.0009*
SUW LCS	0.2736058	0.071283	3.84	0.0002*
ASW LCS	0.3691659	0.017498	21.10	<.0001*
Missile Boats	0.8632445	0.025345	34.06	<.0001*
Submarines	0.0651678	0.020281	3.21	0.0015*
Merchants	-0.012944	0.098338	-0.13	0.8954
57mm Pk	-0.794563	1.016705	-0.78	0.4353
.50 Cal Pk	-0.335862	1.016844	-0.33	0.7415
RAM Pk	-0.724779	1.016942	-0.71	0.4767
LCS Pd	0.3415489	1.016866	0.34	0.7373
SUW Helo Pd	-0.089549	1.018362	-0.09	0.9300
Hellfire Pk	-0.169102	1.01673	-0.17	0.8680
NLOS Pk	1.1655037	1.016865	1.15	0.2529
30mm Pk	0.8419957	1.01715	0.83	0.4086
ASW Helo Pd	0.0076011	1.016688	0.01	0.9940
Blue Torpedo Pk	8.8222325	1.017024	8.67	<.0001*
USV Pd	0.301643	1.016699	0.30	0.7670
RMV Pd	0.2586875	1.016743	0.25	0.7994

- Mean(Total Red Casualties)
  - Identifies SUW LCS, ASW LCS, Missile Boats, Submarines, and Blue Torpedo Pk as statistically significant
  - These parameters explain 88 per cent of the variance in mean(total red casualties)



# ASW Scenario Analysis



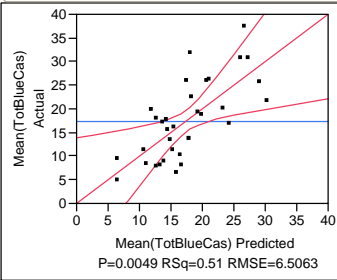
- Mean(Total Red Casualties)
  - High means are good
  - Suggests that 7 ASW LCS provides more red casualties on average
  - Blue Torpedo Pk greater than 0.79 provide higher red casualties when there are 7 or more ASW LCS and 15 or more Missile Boats

40



# ASW Scenario Analysis

Actual by Predicted Plot



Summary of Fit

RSquare	0.512404
RSquare Adj	0.381128
Root Mean Square Error	6.506328
Mean of Response	17.38137
Observations (or Sum Wgts)	34

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	1156.6362	165.234	3.9033
Error	26	1100.6398	42.332	Prob > F
C. Total	33	2257.2760		0.0049*

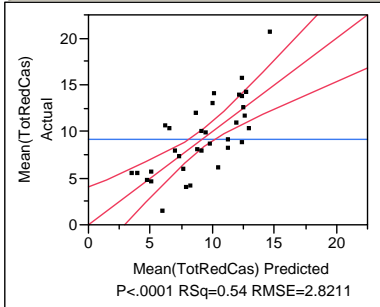
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-41.38054	13.70459	-3.02	0.0056*
Hellfire Pk	20.427108	9.14426	2.23	0.0343*
RAM Pk	26.446727	9.458703	2.80	0.0096*
SUW Helo Pd	18.755758	7.78344	2.41	0.0233*
RMV Pd	11.99511	8.385883	1.43	0.1645
(Hellfire Pk-0.73865)*(SUW Helo Pd-0.73503)	183.45649	63.76567	2.88	0.0079*
(Hellfire Pk-0.73865)*(RMV Pd-0.75991)	-147.7083	82.98532	-1.78	0.0868
(Hellfire Pk-0.73865)*(LCS Pd-0.75124)	-62.01953	62.01724	-1.00	0.3265

- Mean(Total Blue Casualties) from Effects Screening
  - $6 \leq \text{Total LCS} \leq 10$  Data Set
  - Looking at sensors and weapon systems only
  - Identifies Hellfire Pk, RAM Pk, and SUW Helo Pd as statistically significant
  - These parameters with the interaction term explain 51 per cent of the variance in mean total blue casualties in the data where  $6 \leq \text{Total LCS} \leq 10$



Actual by Predicted Plot



Summary of Fit

RSquare	0.541722
RSquare Adj	0.512155
Root Mean Square Error	2.821075
Mean of Response	9.222549
Observations (or Sum Wgts)	34

Analysis of Variance

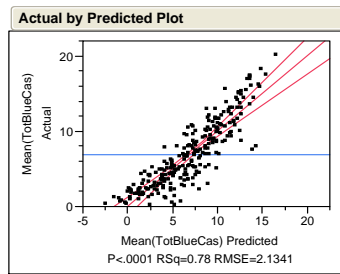
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	291.63365	145.817	18.3222
Error	31	246.71240	7.958	Prob > F
C. Total	33	538.34605		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	1.6386205	2.552077	0.64	0.5255
USV Pd	9.9952454	3.33719	3.00	0.0054*
(Blue Torpedo Pk-0.72803)*(SUW Helo Pd-0.73503)	-131.1866	27.02523	-4.85	<.0001*

- Mean(Total Red Casualties)
  - $6 \leq \text{Total LCS} \leq 10$  Data Set
  - Looking at sensors and weapon systems only
  - Identifies USV Pd and an interaction term as statistically significant
  - These two parameters explain 54 per cent of the variance in mean total red casualties for the  $6 \leq \text{Total LCS} \leq 10$  Data Set

## C. MIW SCENARIO



### Summary of Fit

RSquare	0.781355
RSquare Adj	0.765803
Root Mean Square Error	2.134058
Mean of Response	6.926459
Observations (or Sum Wgts)	257

### Analysis of Variance

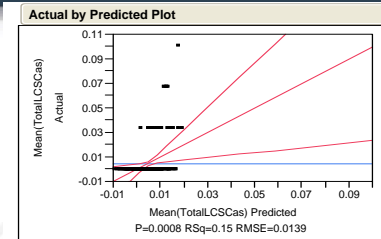
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	3889.7191	228.807	50.2409
Error	239	1088.4543	4.554	Prob > F
C. Total	256	4978.1734		<.0001

### Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-4.487733	2.444096	-1.84	0.0676
MIW LCS	0.3478745	0.015814	22.00	<.0001 *
SUW LCS	0.1393282	0.064428	2.16	0.0316 *
Missile Boats	0.5642299	0.030556	18.47	<.0001 *
Mines	0.0118179	0.002553	4.63	<.0001 *
Merchants	-0.027347	0.088865	-0.31	0.7586
LCS Pd	-0.141796	0.918923	-0.15	0.8775
MIW Helo Pd	-0.852789	0.919115	-0.93	0.3544
SUW Helo Pd	0.4193247	0.918962	0.46	0.6486
NLOS Pk	0.6297063	0.918822	0.69	0.4938
57mm Pk	0.5866288	0.920275	0.64	0.5244
30mm Pk	0.799737	0.918903	0.87	0.3850
RAM Pk	0.4907458	0.918877	0.53	0.5938
.50 Cal Pk	0.5885526	0.919132	0.64	0.5226
Clearance Pk	-1.843773	0.918889	-2.01	0.0459 *
Hellfire Pk	-0.788637	0.919563	-0.86	0.3920
MIW USV Pd	-0.489938	0.918855	-0.53	0.5944
MIW RMV Pd	0.6943396	0.918776	0.76	0.4506

# MIW Scenario Analysis

- Mean(Total Blue Casualties)
  - Identifies MIW LCS, SUW LCS, Missile Boats, Mines, and Clearance Pk as statistically significant
  - These five parameters explain 78 per cent of the variance in mean total blue casualties



### Summary of Fit

RSquare	0.154493
RSquare Adj	0.094353
Root Mean Square Error	0.013872
Mean of Response	0.004669
Observations (or Sum Wgts)	257

### Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	0.00840396	0.000494	2.5689
Error	239	0.04599292	0.000192	Prob > F
C. Total	256	0.05439689		0.0008

### Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.0266113	0.015888	1.67	0.0952
MIW LCS	-0.000235	0.000103	-2.29	0.0227 *
SUW LCS	-0.000265	0.000449	-0.63	0.5274
Missile Boats	0.0006994	0.000199	3.52	0.0005 *
Mines	6.4762e-5	1.659e-5	3.90	0.0001 *
Merchants	-0.000842	0.000578	-1.46	0.1464
LCS Pd	-0.003999	0.005973	-0.67	0.5038
MIW Helo Pd	-0.002026	0.005975	-0.34	0.7348
SUW Helo Pd	-0.003829	0.005974	-0.64	0.5222
NLOS Pk	-0.003106	0.005973	-0.52	0.6036
57mm Pk	-0.012106	0.005982	-2.02	0.0441 *
30mm Pk	0.0012483	0.005973	0.21	0.8346
RAM Pk	-0.002077	0.005973	-0.35	0.7283
.50 Cal Pk	-0.00207	0.005975	-0.35	0.7294
Clearance Pk	-0.004911	0.005973	-0.82	0.4118
Hellfire Pk	0.0043964	0.005978	0.74	0.4628
MIW USV Pd	-0.004628	0.005973	-0.77	0.4392
MIW RMV Pd	-0.003726	0.005972	-0.62	0.5333

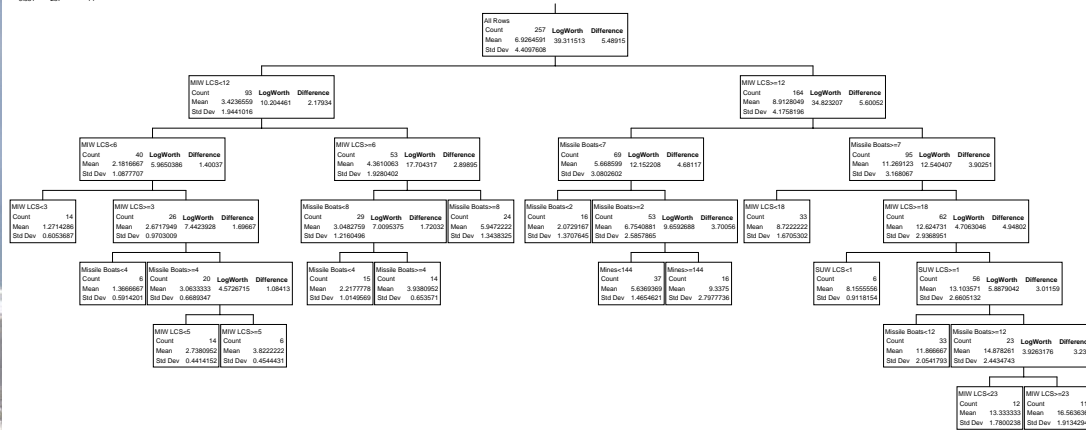
- Mean(Total LCS Casualties)
  - Identifies MIW LCS, Missile Boats, Mines, and 57mm Pk as statistically significant
  - These four parameters explain 15 per cent of the variance in Mean(Total LCS Casualties)

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# MIW Scenario Analysis

RSquare: 0.881  
N: 257  
of Splits: 14



- Mean(Total Blue Casualties)
  - Missile Boats guarding the mines have a greater impact on blue casualties than the mines
  - Suggests that approximately 6 MIW LCS help keep blue casualties low when there are up to 8 Missile Boats
  - Supports the squadron size of 6 – 10 LCS

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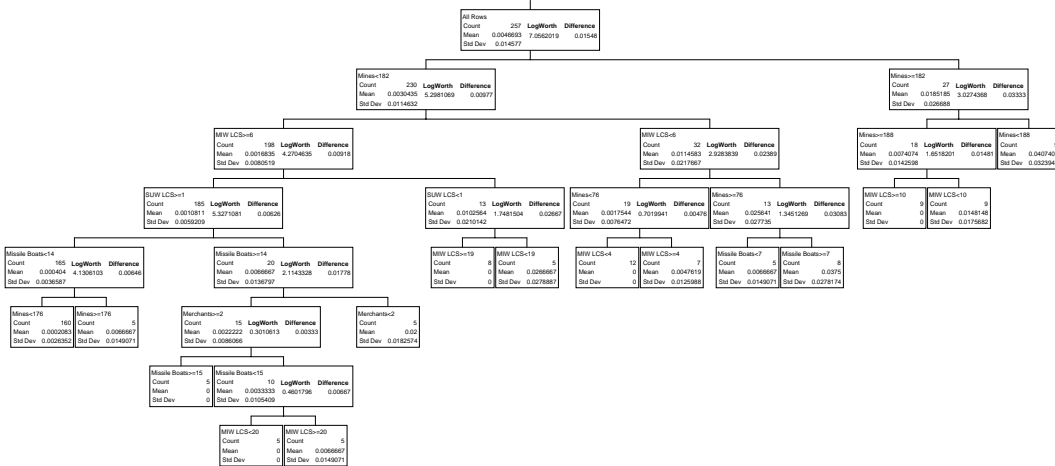
# MIW Scenario Analysis

Number  
of Splits  
14

RSquare  
0.532

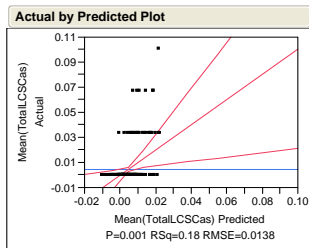
257

14



- Mean(Total LCS Casualties)
  - Mines have greater impact on LCS casualties
  - Minimum of 6 MIW LCS reduces LCS casualties when there are less than 182 mines
    - When there are 6 or more MIW LCS at least 1 SUW LCS reduces LCS casualties
    - Not including a SUW LCS causes a need of at least 19 MIW LCS





**Summary of Fit**

RSquare	0.179159
RSquare Adj	0.101986
Root Mean Square Error	0.013814
Mean of Response	0.004669
Observations (or Sum Wgts)	257

**Analysis of Variance**

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	22	0.00974569	0.000443	2.3215
Error	234	0.04465120	0.000191	Prob > F
C. Total	256	0.05439689		0.0010 *

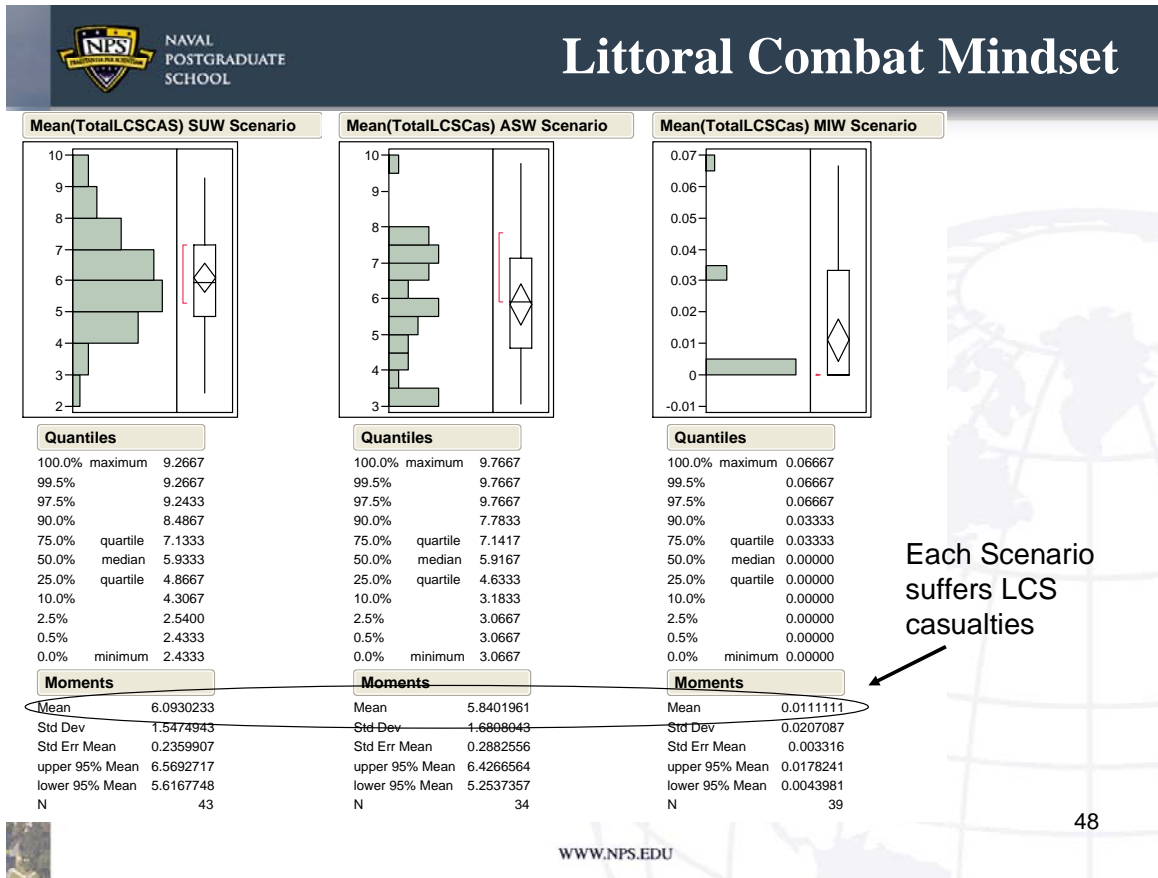
**Parameter Estimates**

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.0262459	0.007131	3.68	0.0003 *
57mm Pk	-0.023588	0.00925	-2.55	0.0114 *
(57mm Pk-0.75001)*(Clearance Pk-0.75001)	0.0409345	0.041786	0.98	0.3283
(LCS Pd-0.75001)*(LCS Pd-0.75001)	-0.062204	0.046226	-1.35	0.1797
(MIW RMV Pd-0.75001)*(NLOS Pk-0.75001)	-0.078522	0.044551	-1.76	0.0793
(57mm Pk-0.75001)*(MIW Helo Pd-0.75001)	-0.069605	0.039183	-1.78	0.0770
(MIW Helo Pd-0.75001)*(MIW Helo Pd-0.75001)	-0.121427	0.047282	-2.57	0.0108 *
(LCS Pd-0.75001)*(LCS Pd-0.75001)*(LCS Pd-0.75001)	-0.011152	0.149875	-0.07	0.9407
(57mm Pk-0.75001)*(Clearance Pk-0.75001)*(Hellfire Pk-0.75001)	0.6922165	0.299527	2.31	0.0217 *
(Clearance Pk-0.75001)*(Clearance Pk-0.75001)*(Hellfire Pk-0.75001)	0.7708877	0.282034	2.73	0.0067 *
(MIW USV Pd-0.75001)*(MIW USV Pd-0.75001)*(Hellfire Pk-0.75001)	-0.912387	0.294377	-3.10	0.0022 *
(57mm Pk-0.75001)*(SUW Helo Pd-0.75001)*(Hellfire Pk-0.75001)	0.1087525	0.327118	0.33	0.7398
(57mm Pk-0.75001)*(Hellfire Pk-0.75001)*(Hellfire Pk-0.75001)	0.5126974	0.344301	1.49	0.1378
(SUW Helo Pd-0.75001)*(Hellfire Pk-0.75001)*(Hellfire Pk-0.75001)	-0.31323	0.207813	-1.51	0.1331
(57mm Pk-0.75001)*(MIW USV Pd-0.75001)*(MIW RMV Pd-0.75001)	-0.289383	0.319865	-0.90	0.3666
(MIW USV Pd-0.75001)*(MIW RMV Pd-0.75001)*(MIW RMV Pd-0.75001)	-0.395988	0.215892	-1.83	0.0679
(57mm Pk-0.75001)*(57mm Pk-0.75001)*(NLOS Pk-0.75001)	-0.182096	0.311509	-0.58	0.5594
(MIW USV Pd-0.75001)*(MIW USV Pd-0.75001)*(NLOS Pk-0.75001)	-0.496276	0.265644	-1.87	0.0630
(MIW USV Pd-0.75001)*(SUW Helo Pd-0.75001)*(NLOS Pk-0.75001)	-0.54054	0.359677	-1.50	0.1342
(Hellfire Pk-0.75001)*(Hellfire Pk-0.75001)*(NLOS Pk-0.75001)	0.3605902	0.29942	1.20	0.2297
(Clearance Pk-0.75001)*(Clearance Pk-0.75001)*(MIW USV Pd-0.75001)*(SUW Helo Pd-0.75001)	-0.428785	1.570634	-0.27	0.7851
(57mm Pk-0.75001)*(57mm Pk-0.75001)*(SUW Helo Pd-0.75001)*(Hellfire Pk-0.75001)	0.8868304	1.623743	0.55	0.5855
(57mm Pk-0.75001)*(Clearance Pk-0.75001)*(Clearance Pk-0.75001)*(MIW RMV Pd-0.75001)	1.8909118	1.459144	1.30	0.1963

## MIW Scenario Analysis

- Mean(Total LCS Casualties) from Effects Screening
  - Looking only at sensors and weapon systems
  - 57mm Pk is the only weapon system identified as statistically significant by itself

## D. FURTHER INSIGHTS



## LIST OF REFERENCES

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